WEB MATERIAL EFFECTS ON WRINKLING INSTABILITY
EXPERIMENTAL AND COMPUTER ANALYSIS

By

VINAY K. NILKANTH

Bachelor of Science

V.J.T.I., University of Bombay

Bombay, India

1985

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
MAY, 1987

Thesis
1987
N712w
cop. 2

OKLAHOMA STATE
UNIVERSITY
LIBRARY

WEB MATERIAL EFFECT ON WRINKLING INSTABILITY

EXPERIMENTAL AND COMPUTER ANALYSIS

Thesis Approved:

Delcie R Durham
Thesis Adviser

R L Lowery

P. K. Good

Norman N. Durham
Dean of the Graduate College

1275700

PREFACE

Permanent creases or wrinkles in a web are costly, due to large amount of wastage associated with the wrinkles. This makes it necessary to investigate wrinkle formation from all aspects. This project especially involves investigation into the roll that the web material and its thickness have in the generation of a wrinkling instability. It involves the material behavior of the web, including possible elastic anisotropy, and web thickness on the development of the shear and longitudinal wrinkles. A simple computer model was developed on NASTRAN to aid the experimental outcomes.

I deeply wish to acknowledge the assistance, encouragement and advise received from my thesis adviser, Dr. D.R. Durham. I would like to thank the Web Handling Research Center for the research assistantship support given to me throughout this research which made my studies at Oklahoma State University possible.

I would also like to thank my committee, Dr. J. K. Good and Dr. R. L. Lowery for their help and assistance in the various phases of this research.

I am thankful to my friends, Mr. Jeff Jacobson, Mr. Mohan Sankaran, Mr. R.K. Perrati for their stimulative discussions on the subject.

I cannot forget the constant encouragement, moral and

financial support given to me by my beloved parents, Mrs. & Mr. K.S. Nilkanth and my two sisters Ms. Rekha and Ms. Geeta Nilkanth.

TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure | Page

LIST OF SYMBOLS

Symbol	
Tg	Glass Transition Temperature
Tm	Melting Point Temperature
MD	Machine Direction of Rolling
TD	Transverse Direction of Rolling
E	Young's Modulus of Elasticity
e	Engineering Strain
e(t)	True Strain
s	Engineering Stress
s(t)	True Stress
le	Final Length
lo	Original Length
w	Original Width
w(r)	Reduced Width
t	Thickness
A	Area

CHAPTER I

INTRODUCTION

The term "WEB" is used to describe materials that are manufactured and processed in continuous, flexible, strip form. The materials that are handled as webs cover a broad spectrum; from extremely thin plastics and papers, to textiles, metals and composites. The widespread use of web processing arises not only from the form of the materials, but also it's economy and the higher levels of consistency of product quality generally achievable through its use. Much of the knowledge base on web handling and processing is of an empirical nature and often proprietary. The lack of an extensive fundamental knowledge base on the web handling processes is a major deterant to the effective future developments and optimization of the web handling equipment. As a part of this basic understanding of web handling, the behavior of the web material itself, in the static and dynamic modes, must be clearly defined.

In this research emphasis is placed on the static and dynamic modeling and the computer simulation of the web material behavior. Specifically it is involved with the measurement of the mechanical properties of the different web materials, and an investigation into the lateral and the longitudinal anisotropic properties of these web materials. It is also concerned with the propensity of the different web materials to exhibit wrinkling instability.

Permanent creases or wrinkles are costly defects that may occur in web handling. The formation of a wrinkle may be directly related to the geometry of the web handling system, for example, the length to width aspect ratio of the unsupported web. Wrinkles may also depend upon the thickness of the web and the stiffness of the web material. It is necessary to determine the role that the material anisotropy may have in the wrinkle formation. The elastic buckling of the web may have a direct relationship to the degree of anisotropy of the elastic modulus and the yield strength of the web material. The elastic anisotropy may be in the plane or through the thickness of the web depending on the processing sequence and the material itself.

Previous research by Good and Papandreadis (1), has indicated that the wrinkling instabilities in the polymeric materials are an effect of the aspect ratio and the number of wrinlkes are inversely related to the aspect ratio. This work involved a computer simulation technique developed to model the dynamic web behavior in the unsupported web.

A computer model of the web material is developed in order to determine the effects of material properties and the thickness upon the wrinkle generation and the stress distribution. The model also determines the effects of the variations in the aspect ratio of the web, the boundary conditions at the modeled roller positions and directional material properties, i.e. the degree of anisotropy. The stresses developed in the web dictates whether the elastic or elastic-plastic conditions exist. The elastic modulus and the elastic limit (yield strength) of polymers, metals and paper differ significantly. It is therefore necessary to establish the role the material elasticity and elastic-plastic transition may play in the wrinkle generation.

Web Materials

The following materials were of prime interest during this research work: Polypropylene, Polyethylene plastics, Papers (Aluminum coated and Kraft), Aluminum foils.

Polypropylene and Aluminum foils were considered for the anisotropic properties in the machine direction (MD) and transverse direction (TD). Also biaxial and triaxial loading conditions were considered as a function of web material thickness. Static and dynamic tests were performed on these materials to evaluate the possible material effects on the longitudinal and shear wrinkles in the web.

The material behavior of the web, was investigated, including the material vs geometry introduced instabilities, the effects of elasticity and the possible elastic anisotropy on the wrinkle generation. A computer model was developed to investigate the effect of these variables associated with the web handling.

Computer Model

A finite element approach was considered throughout this research to develop an understanding of the stress distributions and the strain values in the web material. A finite element software package NASTRAN, on the IBM 3081k mainframe computer was used for the computer modeling of the static and dynamic web with the variables associated with web handling.

Both static and dynamic cases were considered for these models. In the early stages of this research standard properties of thin polyethylene material and aluminum foils were used. The static approach involved the simulation done for the static tests performed on the MTS machine while the dynamic tests performed on the MTS machine were modeled using the dynamic model.

For the purpose of better understanding of aspect ratio effects, variable width, variable thickness and variable length were considered. Also simulations of the loads that may be developed by the use of the bowed roller, the inclined roller and the concave roller were investigated.

The models considered during this research work were involved with different boundary conditions and different material properties. The two and three dimensional static models were used with the uniform displacement boundary conditions. Also two and three dimensional dynamic models were used for the following boundary conditions: uniform loading condition along the width, uniformly increasing loading condition along the width, parabolically increasing loading condition along the width, and uniform loading condition across the thickness. The anisotropic material data necessary for the simulation was not available in the literature, and the testing on the MTS material testing machine was necessary to obtain values experimentally.

Experimental Models

Two types of experimental models were prepared, one for the static analysis and other for the dynamic analysis. Static tests involved the investigation into the material properties of the web materials in the MD and TD. These static tests were performed for evaluation of the modulus of elasticity, the degree of directional anisotropy and the elastic-plastic transition of the web materials. These tests were used to generated a sound data base to be used for the computer model of the web. The static test sample sizes were chosen according to the ASTM standards, experimental evaluations and from the considerations of the aspect ratio of the samples.

For the dynamic tests, variable loading conditions were used to investigate the effects of variations in the tension in the web. To evaluate the dynamic effects on the web, variable speed conditions were also tested at the low speed range. These dynamic tests were performed on the polymers, paper and aluminum foils to provide better understanding of the role of web materials in the dynamic behavior of webs.

CHAPTER II

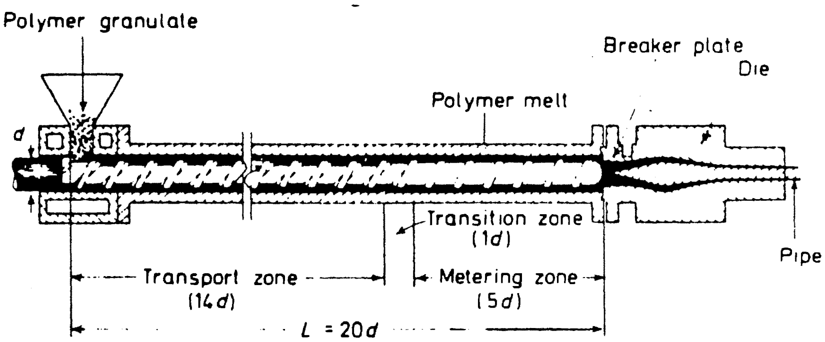
PROCESSING EFFECTS ON WEB MATERIALS

The material properties of the web depend upon the type of manufacturing method and the processing sequence used. The material strength and the directional anisotropy associated with the web material is usually related to the history of the manufacturing method used. The tentering sequence, in the case of polymeric materials for example, affects the tensile properties of the web in MD and TD. The manufacturing methods that affect the web material properties are discussed in this chapter.

Polymeric Materials

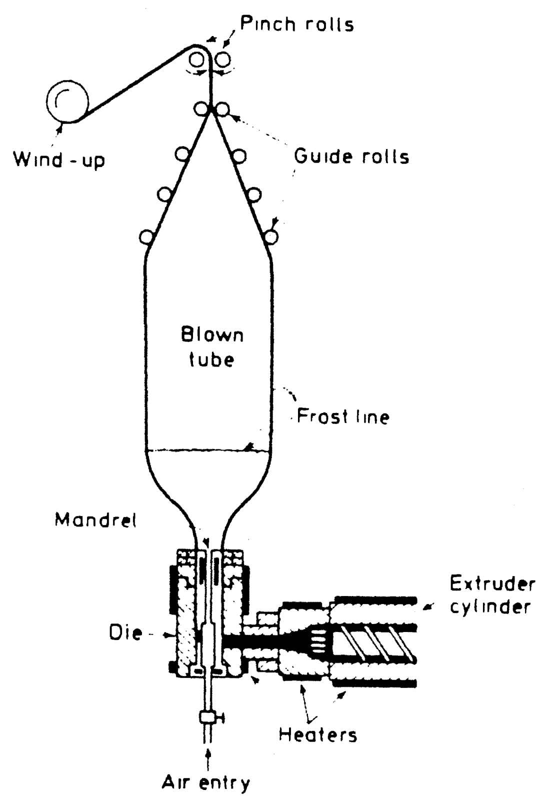
There are fundamentally two methods of extruding polymeric web material, namely, the blown film extrusion and the slit die extrusion. The former method produces tubular film, while the latter results in a flat film.

A typical single screw extruder is shown in Figure 1, consisting of an Archimedean screw which revolves within the close fitting, heated barrel. The granules of plastic are fed through the hopper mounted at one end of the barrel and carried forward along the barrel by the action of the screw. As the granules move along the screw, they are melted by



Source : Briston J. H., "Plastic Films", Ch.8: Manufacturing Methods, Page 64, Figure 8.1

Figure 1 : Typical Single Screw Extruder (L/D = 20)



Source : Briston J. H., "Plastic Films", Ch.8: Manufacturing Methods, Page 65, Figure 8.2

Figure 2 : Blown Film Extrusion

contact with the heated walls of the barrel and by the heat generated due to friction. The screw then forces the molten plastic through the die which determines its final form. The most important component of the extruder is the screw and different designs of the screw are used for extruding different polymers. The extruder screws used are usually characterized by their length to diameter ratio (L/D) and their compression ratio (2).

Blown Film Extrusion

Once in the die, the molten polymer is made to flow around a mandrel and emerges through a ring shaped die opening in the form of a tube. The tube is expanded into a bubble of required diameter by an air pressure maintained through the center of the mandrel. The expansion of this bubble is accompanied by a corresponding reduction in thickness. The extrusion of the tube is usually upwards as shown in Figure 2, but it can be extruded downwards, or even sideways. A uniform thickness of the film is maintained by keeping the air pressure of the bubble constant.

Blown film extrusion is a very complex process and is always associated with many problems, including the variation in the film thickness, surface defects, low tensile strength, low impact strength, hazy film and above all the wrinkling instability. The wrinkling in the film can be due to a variation in the film thickness and can lead to an uneven pull at the pinch rolls (2).

Slit-Die Extrusion

In the flat film extrusion, molten polymer is extruded through a slit-die and then fed into a quenching water bath or onto a chilled roller as shown in Figure 3. In both these cases the essence of the process is rapid cooling of the extruded film and the cooling is therefore applied within a very short distance of the die lip (25mm to 65mm). This short distance is also dictated by the necessity to reduce the 'necking' of the film web, with consequent loss of width (2).

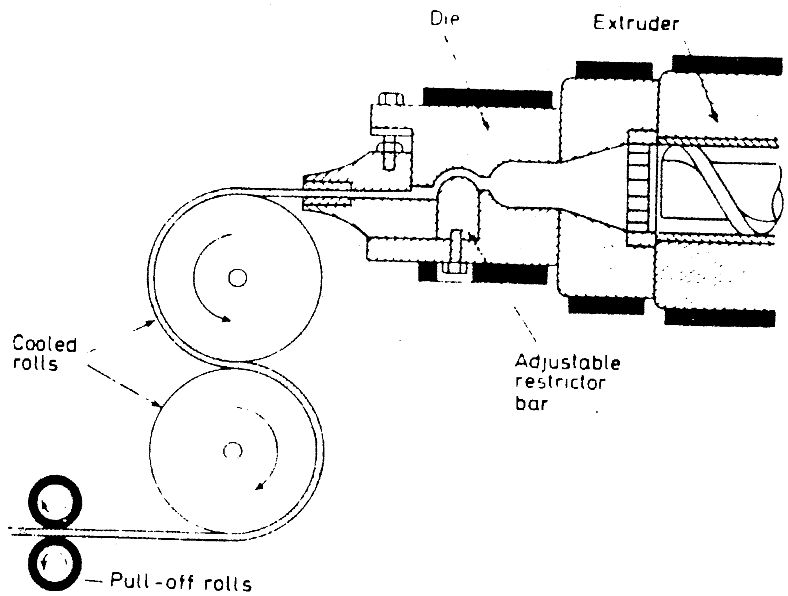
In the chill roll casting method, the melt is extruded onto a chromium plated roller, cored with water for cooling. The slit-die extrusion process is preferred over the blown film extrusion because the films produced have better strength in both MD and TD and the thickness variations associated with slit-die process are small. The variations in the strengths for the slit-die and the blown film processes are indicated in the Table I.

TABLE I

MANUFACTURING METHODS AND TENSILE STRENGTH

Manufacturing Methods	MD (psi)	TD (psi)
Slit-die process	450	380
Blown film process	190	205

Source : Briston J. H., "Plastic Films, Ch.8: Manufacturing Methods, Page 72, Table 8.1"



Source : Briston J. H., "Plastic Films", Ch.8: Manufacturing Methods, Page 69, Figure 8.4

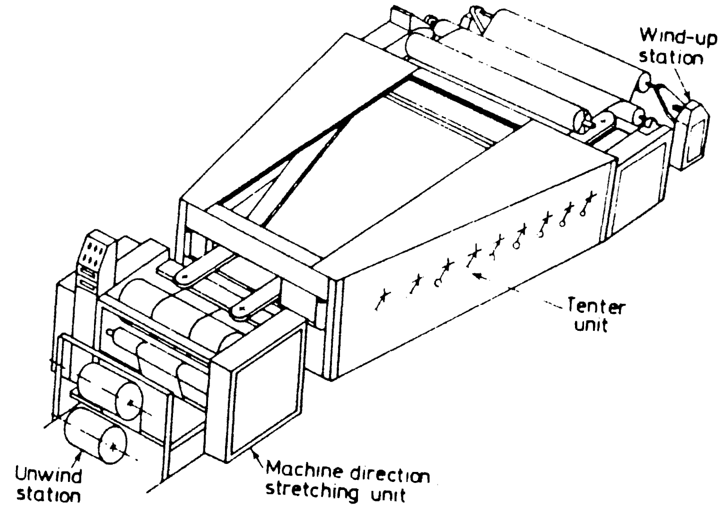
Figure 3 : Film Casting (Slit-Die Extrusion)

Film Orientation Techniques and Anisotropy

The orientation of film by stretching it while heated is widely applied to the films such as polypropylene, nylon, polyethylene and polystyrene to improve the clarity, impact strength and the barrier properties of the film (2).

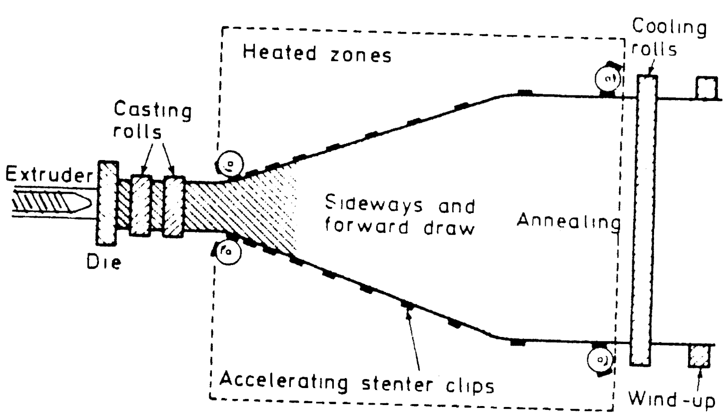
A thick cast film of around 500-600 micron is fed to the system of differential draw rolls, i.e. the rolls running at gradually increasing speeds. These rolls are heated sufficiently to bring the film to a suitable temperature (below the melting point). Under these conditions the film is stretched in the machine direction at a draw ratio which is normally between 4:1 to 10:1. After leaving the draw roll, the film is fed into a tenter frame which consists of two divergent endless belts or chains fitted with the clips. These clips grip the film such that as the film travels it is drawn transversely at a draw ratio similar to that applied in the machine direction. The tentering area is also heated, with accurate control of temperature. The film coming out of the tenter frame is then cooled by passing over a cooling roller, and then wound as shown in the Figure 4.

Oriented films are also available in which this sequence of operations is reversed, i.e. the tenter frame comes first, followed by the differential draw rolls. As shown in the Figure 5, these two operations can also be carried out simultaneously. The film is gripped by its edges as it leaves the casting roll and is then moved forward at an increasing speed while it is stretched transversely by the diverging



Source : Briston J. H., "Plastic Films", Ch.8:
Manufacturing Methods, Page 77, Figure 8.8

Figure 4 : Two Stage Orientation - Flat Film



Source : Briston J. H., "Plastic Films", Ch.8:
Manufacturing Methods, Page 78, Figure 8.9

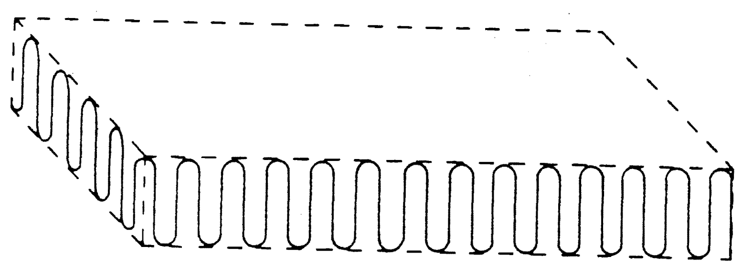
Figure 5 : Simultaneous Orientation Process

grips. It has been observed experimentally that the biaxially oriented plastic films result in less variations in the directional properties of the material than found in the unidirectionally oriented films (2). The process of biaxially orienting the plastic film invariably increases the tensile strength in the MD while decreasing the % elongation. This general behavior has been observed in the different polymer films with minor variations. It has also been observed that the film produced by the blown film extrusion process, if properly controlled, produces near isotropic properties of the material, whereas the tentering of the film leads to anisotropic material properties.

Theory of Polymer Orientation

The polymer orientation is associated with the movement of polymer chains, their orientation and their temperature behavior. It is also dependant on the material response to process variables and the shrinkage behavior of the material.

In the stress-induced orientation, polymer chains are displaced by hot stretching or drawing the bulk material, from a completely random entanglement into a more orderly arrangement parallel to the direction of stretch, as shown in Figure 6. When chain straightening occurs, and with closer packing that accompanies the molecular alignment, mutual attraction force between these chains increases. These forces are particularly large if the chains are symmetrical and/or strongly polar. This increase in the force of attraction and



Source : Ward I. M. ,"Structure and Properties of Oriented Polymers", Ch. 1, Page 17, Figure 7

Figure 6 : Single Crystal and Chain Folding

the unfolding of the polymer chains, result in the increased tensile strength and elastic modulus, which in turn imparts anisotropic properties to the polymers (4). This crystallization of the polymeric material i.e. the molecular orientation during stretching, takes place in the following manner,

Below the glass transition temperatures (Tg), polymer chains are rigid. However at the glass transition temperature these chains gain a degree of freedom and become suceptible to unfolding at higher stress. If the mass of randomly entangled and coiled chains is at a temperature (above Tg) where it may be drawn, such as in biaxial stretching, then as the stress is applied, the polymer chains disentangle and straighten and slip past one another.

There are three components to this process:
E1 is the instantaneous elastic deformation caused by valence angle deformation or bond stretching, and is completely recoverable when the stress is removed; E2 is the molecular alignment deformation caused by uncoiling, resulting in the linear molecular arrangement parallel to the surface which is frozen into the structure when the material is cooled; E3 is the nonrecoverable viscous flow caused by the molecules sliding past one another. E2, the orienting component, is the one desired to be the major component of the stretching process (4).

On the basis of the above theory, some general rules for orienting polymers by stretching can be set forth :

1. The lowest stretching temperature above Tg will give the

greatest orientation and greatest tensile strength at a given percent and rate of stretch as shown in Figure 7.

2. The highest percent stretch will give the greatest orientation at a given temperature and rate of stretch.

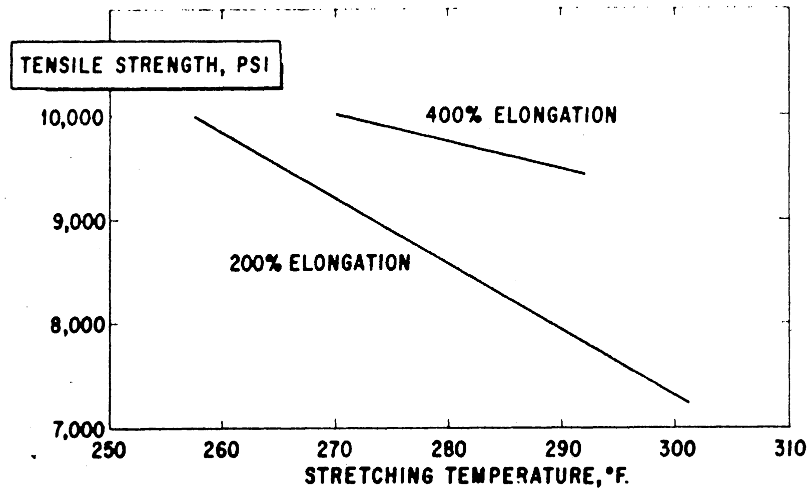
The orientation of the film could be very beneficial in the case of polypropylene material. A non-oriented film at a subzero temperature behaves in a very brittle manner and tends to shatter on impact. On the other hand, biaxially oriented film remains flexible at a low temperature (3).

The property that varies significantly is the dimensional stability. All the polymeric materials have a unique tendency to shrink at a temperature between the glass transition temperature (Tg) and the melting point temperature (Tm). The amount of shrinkage and the temperature of shrinkage initiation depends on the previous stretch and the annealing history of the film as shown in Figure 8.

It is also observed that as the density of the polymer increases, hardness, abrasion resistance, tensile strength, rigidity, heat resistance, chemical resistance and surface gloss also increases. Whereas decreasing density leads to increase in toughness, stress-crack resistance, clarity, flexibility and elongation. Decrease in the density also reduces creep failure and mold shrinkage.

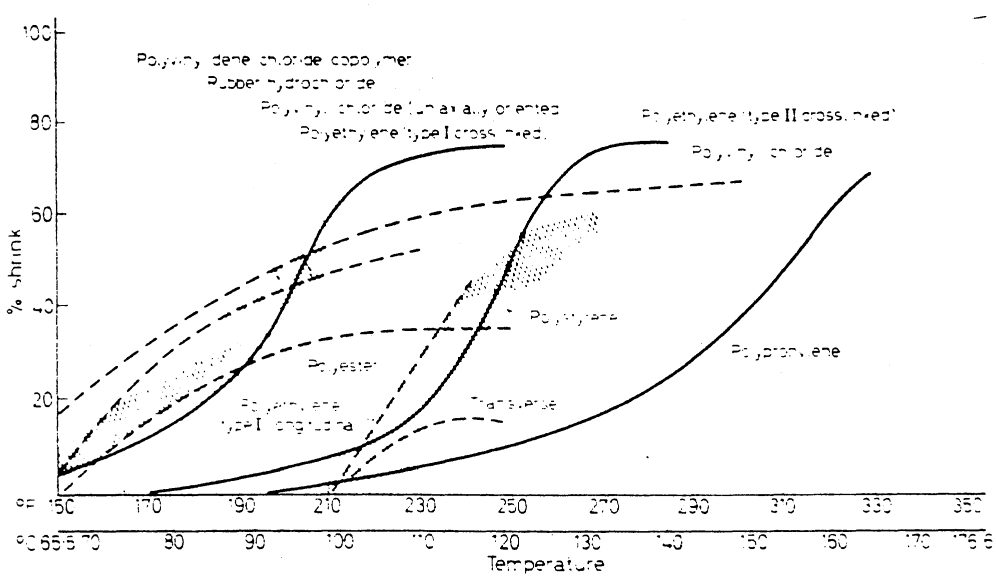
Shrinkage behavior of Oriented Amorphous Plastics

Oriented polystyrene film typifies the behavior of biaxially oriented non-crystalline polymers. This material,



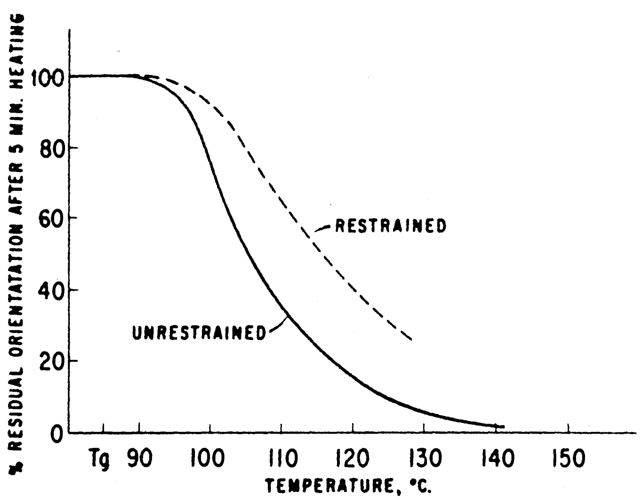
Source : Park W. R. R., "Plastics Film Technology", Ch. 2: Methods of Manufacturing, Page 28, Figure 2.19

Figure 7 : Temperature and % Elongation Effect on Tensile Strength of Oriented Film



Source : Rigby H. A. , "Production, Properties and Packaging Applications of Polypropylene Film", Page 77, Figure 3.8

Figure 8 : % Shrink vs. Film Temperature



Source : Park W. R. R., "Plastics Film Technology", Ch. 2: Methods of Manufacturing, Page 30, Figure 2.20

Figure 9 : Orientation Loss on Heating for Polystyrene

on gradual unrestrained heating, shows only a thermal expansion until the glass temperature, Tg, is reached. At the temperatures above Tg, the material will shrink and the rate of shrink increases with an increase of temperature.

When a sample of biaxially oriented polystyrene film is heated and restrained from shrinking, it loses orientation as shown in Figure 9. Also a restrained sample shows an orientation release stress when heated. That is the material exerts a positive pull on the restraining clamps in its attempt to shrink. The magnitude of this released stress is related to the original film stretching condition and this released stress is the characteristic of the orientation level (4). It is to be noted that it is not possible to stabilize this oriented film of amorphous material against the shrinkage above the glass transition temperature.

Shrinkage Behavior of Oriented Crystalline Plastics

The main difference between the crystalline and the noncrystalline polymers in oriented form is that the crystalline polymers can be stabilized against gross shrinkage above their glass transition temperatures. Thus we can have two films of the same material, same degree of orientation but with greatly different shrinkage properties.

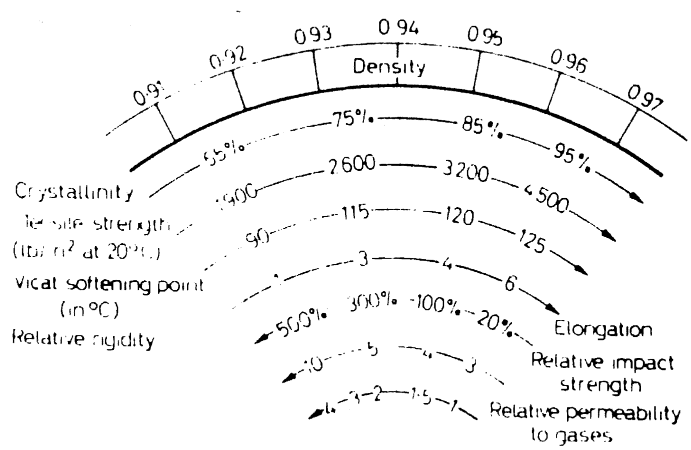
For example, if polyethylene terephthalate is melted at 290 c and then rapidly quenched to below its Tg, 69 c, an essentially amorphous material is obtained. If it is rapidly stretched at 90 c and then quenched, this material shows essentially the same behavior on reheating as the oriented polystyrene i.e. when heated unrestrained above Tg, it starts to shrink, and its shrink rate increases to a maximum value as the original stretch temperature is either approached or exceeded. Under these conditions the polyethylene terephthalate behaves like any other amorphous material.

When an extra processing step is introduced into the forgoing melt, quench, heat, stretch, and quench sequence, the film can be obtained which gives the identical physical properties as that at the room temperature but with negligible shrinkage at 100 c. This extra step involves restraining the film and heating the film to 150-225 c, and then quenching as before. This heat treatement stabilizes the film for a better heat shrinkage characteristic (5), thus it is possible by heat treatment of the crystallized polymers to control the shrinking problem above glass transition temperature as shown in Figure 10.

A second important factor in stabilization of crystallized polymer is the difficulty of amorphising crystalline film. Thus for each oriented crystallized material the relationship between temperature and rate of crystallization should be known.

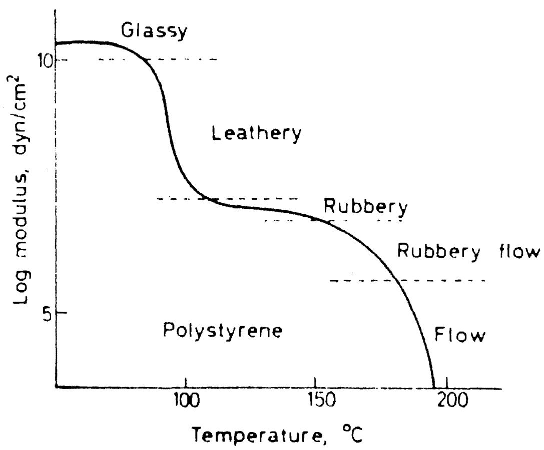
Mechanical Behavior of Polymeric Films

The variation of the modulus of elasticity with respect to the temperature is shown in Figure 11. In the glassy region, the long polymer molecule is frozen, with the atoms



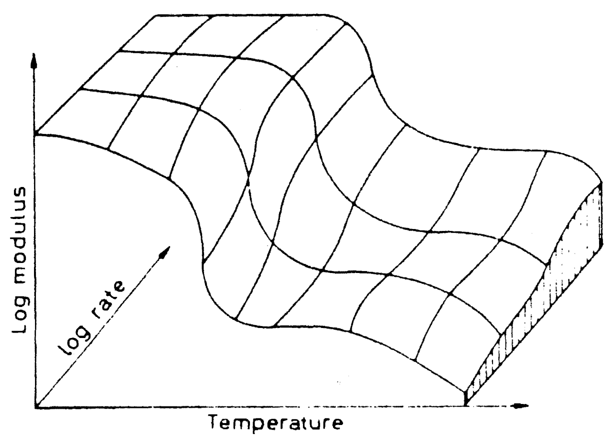
Source : Ladbury J. W. , "Production, Properties and Packaging Applications of Polyethylene Film", Page 24, Figure 2.1

Figure 10 : Effect of Crystallinity on Properties of Polyethylene



Source : Rigby H. A. , "Physical Properties of Polymer Films", Page 148, Figure 7.1

Figure 11 : Variation of Modulus of Polystyrene with Temperature



Source : Rigby H. A. , "Physical Properties of Polymer Films", Page 150, Figure 7.2

Figure 12 : Modulus as a Function of Rate and Temperature

vibrating about fixed positions as in any rigid solid (3).

In the transitional leathery region, where the modulus is changing rapidly with temperature, short range diffusion of the segments of the polymer chain takes place, but any movement is restricted to individual atoms or two or three neighboring atoms and the molecule as a whole does not move.

In the rubbery region, the modulus is fairly constant. Here the short range motion of the polymer segment occurs and the cooperative movement of the adjacent segments takes place rapidly.

In these three regions, glassy, leathery and rubbery, the Young's Modulus of Elasticity of commercially available polymers is independent of the molecular chain length. In the rubbery flow region, the motion of molecules as a whole becomes important as a result of slippage of entanglements, while in the leathery region of flow, changes in the entire molecule takes place quicker than the rate of test and there is little elastic recovery at this time scale.

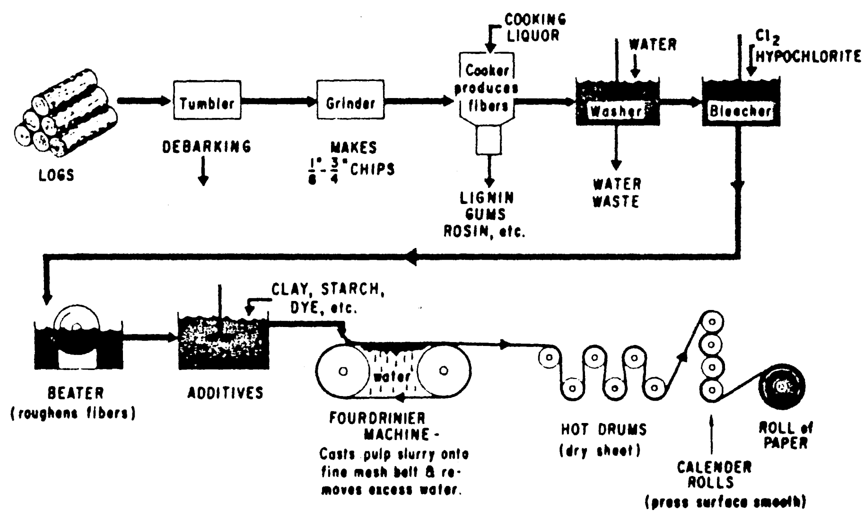
The Modulus of Elasticity in case of polymers is rate dependent, because the major changes in the modulus take place due to the molecular activity occurring at the large magnitudes at rates faster than the test rates. The Figure 12 shows the variation of the Modulus of Elasticity with respect to the temperature and the rate of test. In this figure the graph surface is decided by the material properties such as, the crystallinity of the polymer, secondary glass transition temperature, cross linking of the polymers and the rate of test performed. It is clear from this graph that the relationship between the modulus of elasticity and the temperatute and strain rate is non-linear and is much complex is nature.

Non-Polymeric Materials

Papermaking

As discussed earlier the anisotropic material properties of the web are the function of the method of manufacturing. In the case of paper webs the material of the web and the coating used influences the material properties more than the manufacturing process itself. The anisotropic properties of the paper webs are generally associated with the moister content of the paper, thickness of the paper and the paper quality (roughness). All these factor are indirectly controlled by the process used for the manufacturing of paper webs. Also the mechanical behavior of the paper web is directly related to the type of raw material used, for example the type of wood or grass used.

Paper consists largely of pure cellulose fibers, which have been seperated from other components which constitutes various types of wood. These individual and seperate fibers are recombined to give paper of various qualities. The wide spectrum of paper properties which are available result from a great variety of raw materials, additives, processing, coatings and finishing variables that can be used (4). The conventional papermaking process is shown in the Figure 13.



Source : Park W. R. R., "Plastics Film Technology", Ch. 2: Methods of Manufacturing, Page 10, Figure 2.1

Figure 13 : Conventional Papermaking Process

The paper processing variables associated with the paper making process are given in Table II.

TABLE II

PAPER PROCESSING VARIABLES

1.	Material Type	Newsprint, Coated Paper, Kraft
2.	Roller Material	Steel, Aluminum, Rubber, Coated (Moly/Tungsten).
3.	Speed	2000 - 8000 fpm
4.	Tension	1 - 10 pli
5.	Web Width	100 in. - 300 in.
6.	Roll Diameter	36 in. - 108 in.

<u>Aluminum Foil</u>

Most of the metals can be made into thin foils by adapting of steel rolling techniques. So far, only aluminum foils have been found widespread utility. This material, in thicknesses down to 0.0002 in., is widely used in packaging because, when properly handled, it is completely impermeable to water, gases, odors and solvents. The thinner gauges, by themselves, are quite weak and easily ruptured, but when combined with plastic films such as polyvinylidene chloride or polyester, or when extrusion coated with polyolefins they become functional packaging materials that provide the best possible barrier (4).

Aluminum foil is made by passing hot sheet through a series of hot, highly polished, precision finished metal roll nips of ever decreasing nip opening until the desired final thickness of foil is obtained.

Foil is generally made from nearly pure aluminum. Some grades will be alloyed with up to 1-1.5% manganese where higher strength is needed.

Depending on the degree of tempering and chemical composition, foils are generally made within the Ultimate Tensile Strength of 10000-30000 psi.

CHAPTER III

EXPERIMENTAL ANALYSIS : STATIC AND DYNAMIC

As a part of the basic understanding of the web handling process, the behavior of the web material itself, in the static and dynamic modes, must be clearly understood. This fundamental understanding involves the measurement of the mechanical properties of different web materials, and an understanding of the directional anisotropy of these web materials. It is also concerned with the propensity of the different web materials to exhibit the wrinkling instability. The effects of the aspect ratio on the wrinkling instability in the web processing should be clearly defined.

The wrinkle formation may be related to the elastic properties of the material and possible anisotropy of the modulus of elasticity. It may also be related to the elastic-plastic transition characteristics of the web materials. The speed and the tension effects coupled with the material properties are investigated. This provides the basic information base required for the more realistic computer modeling of the static and dynamic web. Static and dynamic testing of web materials was performed to provide this information.

The static tests involved the tensile testing of the web materials in specially designed grips to determine the stress-strain behavior in both the elastic and the plastic regions of the web material, under the different conditions of strain rate. The dynamic testing was concerned with the behavior of a web moving at low speed across a pair of rollers under various loading conditions. Both the static and the dynamic tests were performed on the Materials Testing (MTS) machine as shown in Figure 14.

Different materials were tested with variations in the thickness and orientation to determine their effects on the static tests. The variations in the load and speed were performed on various materials in the dynamic tests.

For both the static and dynamic tests the MTS machine was used with a 500 lb. load cell and an HP plotter. The high sensitivity of the 500 lb. load cell was sufficient to monitor any load variations.

Static Tests

The static tests were performed on the polypropylene, polyethylene, aluminum foils and the paper materials to determine the material effects on the wrinkling instability. These static tests were performed according to the ASTM (8,9) standard D882-83 for the tensile testing of thin plastics. The grips used for the static tests were specially designed and the rubber linning material was chosen according to ASTM specification given in the standard. According to the D882-83 standard a specimen of 1 in. X 8 in. (w X l) is to be tested.

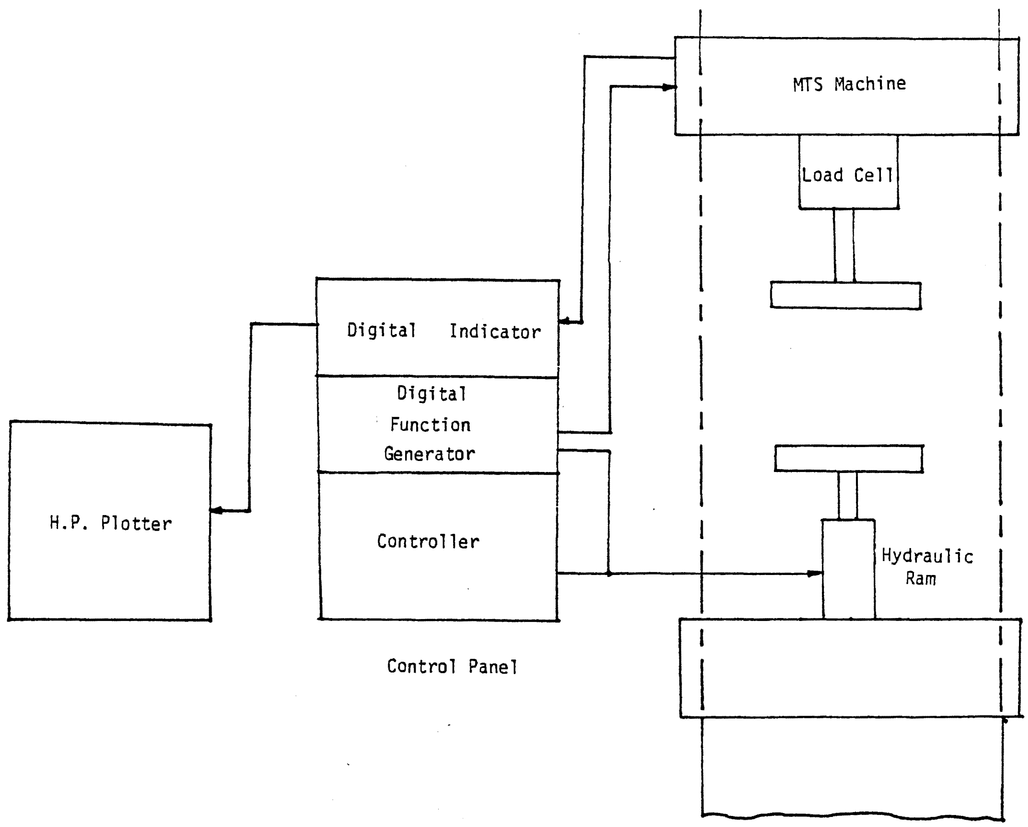


Figure 14 : Schematic Diagram of Machine Setup.

These samples are basically straight strips of material without any reduced area.

During the testing of these samples it was observed that this specimen size was satisfactory for a 0.042 in. thick material (taken from an early stage of the web process), but provided insufficient data for the 1.43 E -03 in. thick (taken from the final roll of the material) sample. This conclusion was drawn from the fact that successful tests were obtained with 90-95% of the thicker samples, resulting in very good repeatable results. Only 5-10% of the thicker samples failed due to end effects when statically tested, whereas almost 50% of the thinner samples failed either by the end effects or by the edge effects giving inaccurate results or little property information.

The variations in the dimension were tested and optimum sample dimensions were found to be 7.0 in. X 4.5 in. for the samples taken, in the direction of stretching, see Table III, and 4.5 in. X 4.5 in. for the samples taken in the direction perpendicular to rolling. These two dimensions were found to be optimum because with these dimensions 80% of the tests provided large strain mechanical bahavior, where the produced results were comparable and predictable, with 20% of the samples failing by end effect or edge effect.

When a sample fails in a distance of about 20% from the end of one of the grips and very close to a grip it is called as an end effect. An end effect could be due to a variety of causes, such as improper gripping of the sample, misalignment

TABLE III

STATIC TEST SPECIMEN SIZES AND MATERIALS

Sizes L X W in.	Materials
1. 7.0 X 4.5	Polypropylene (MD)
4.5 X 4.5	Polypropylene (TD)
2. 7.0 X 5.0	Aluminum Coated Paper (MD)
5.0 X 4.0	Aluminum Coated Paper (TD)
3. 8.0 X 1.0	Paper, Polyethylene (MD)
4. 9.0 X 9.0	Aluminum Foil (MD and TD)

of the chosen specimen, misalignment of the grips, torsional effect by the grips, poorly chosen strain rate, sudden loading of the specimen, internal void defects, tear initiation sites or inappropriate sample size chosen.

The edge effect in a film is usually associated with the inaccurate cutting of film leading to premature tear initiation site.

The grip and specimen setup used for the static testing is shown in Figure 15. The grips were specially designed and lined with the rubber pads to give a better frictional traction to avoid slippage of the sample in the grips and to avoid deforming or crushing the sample. To make the sample 100% slip proof masking tape was used at the end of the specimen.

In Figure 15, the grip # 1 is stationary and is connected to the 500 lb. load cell of the MTS machine. The grip # 2 is

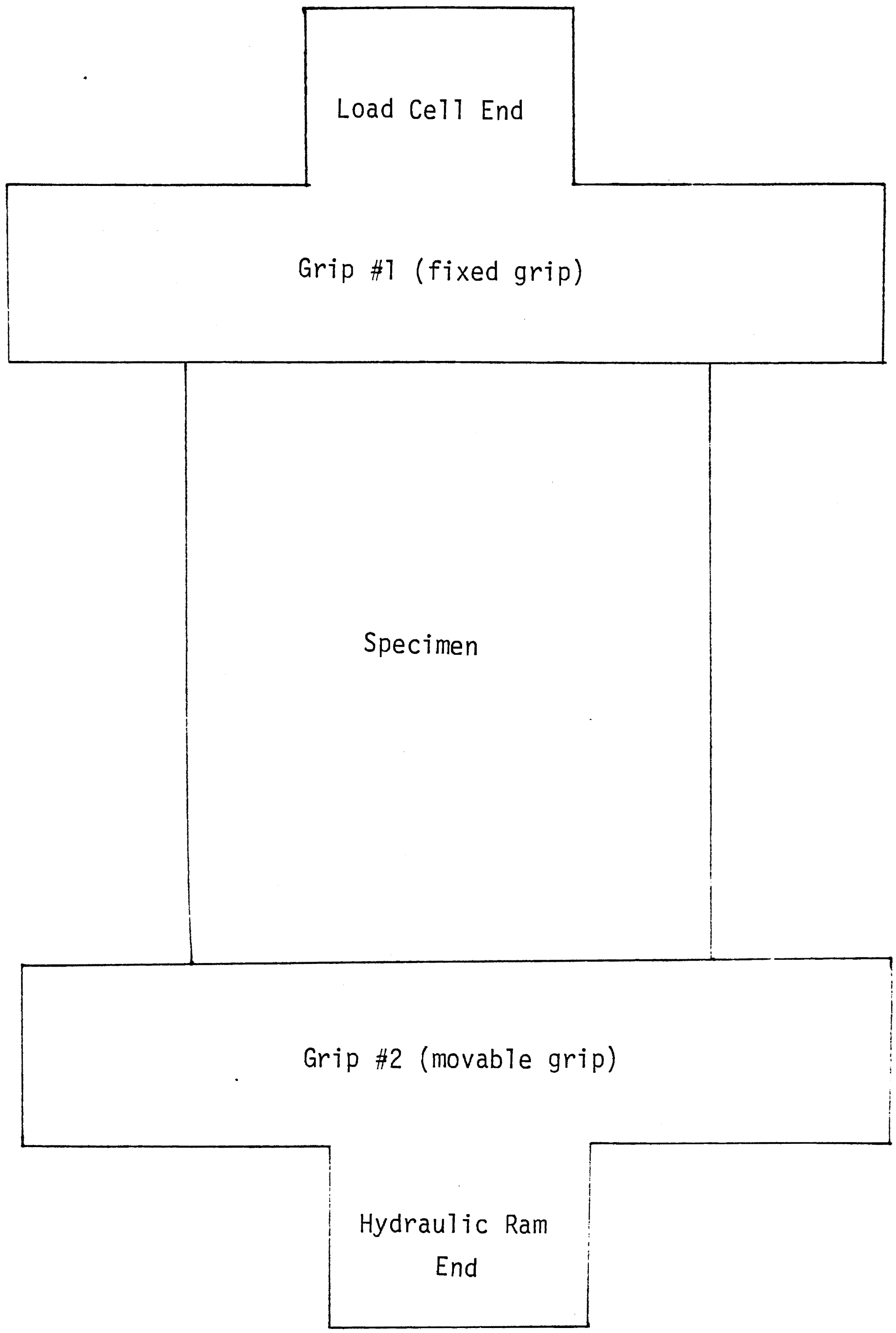


Figure 15 : Grips and Specimen Setup for Static Test

movable and is connected to the hydraulic ram. The hydraulic ram moves at a rate of 4.2 E +02 Hz/sec. to give a speed of 2.38 E -03 in/sec. This crosshead speed was chosen according to the MTS machine specifications for the sample sizes chosen.

During the static testing of the sample the grip 2 moves continuously with a uniform crosshead speed and the material starts to elongate. Initially the elongation is uniform throughout the specimen length and as the elongation continues the specimen starts to neck down in the center portion of the sample and continues elongation, ultimately leading to fracture.

During this process of loading the sample, a hold capability is available on the MTS machine which could be used to stops the hydraulic ram. This is very effective in accurately calculating the scale of the load vs displacement graph. It can be used with metal foils with accuracy; but it cannot be used with the polymeric materials as the polymers have a tendancy to exhibit stress relaxation, a time dependant phenomenon where the load level will reduce with time at a constant strain. Due to this peculiar phenomenon of the polymers, during the static tests only the initial and the final readings were available for scaling of the load vs displacement graph leading to a minor error of scaling. These load vs displacement graphs were then modified as stress vs strain graphs. As the instantaneous values of the width and the thickness reductions were not available these are basically engineering stress vs engineering strain graphs.

The true stress-strain prediction is also given which is based on the calculation of the true stress value for fracture and the actual width and thickness reductions associated with it.

Dynamic Tests

A test setup was designed and constructed to perform the dynamic tests on the MTS machine, as shown in Figure 16. The apparatus consists of a hanger, connecting one roller to the load cell of the MTS machine, a set of the rubber-lined grips attached to the ram, and a channel bracket with a second roller constructed to provide a five foot span between the rollers.

A strip of material, see Table IV, is held in the grip which is attached to the hydraulic ram of the MTS machine. This strip of web material then passes over the first roller connected to the load cell and then over the second roller to which the loads are attached. This gives a free span length of about 5 ft. and an angle of wrap of about 90 degrees. This angle of wrap and span length were kept constant throughout the study.

The cyclic motion of the ram was used which enabled the dynamic testing of web at different low speeds. These low speeds were used to give a fundamental idea of the parameters involved in the dynamic process. The effects of tension in the web were observed by varying the loads supported by the web.

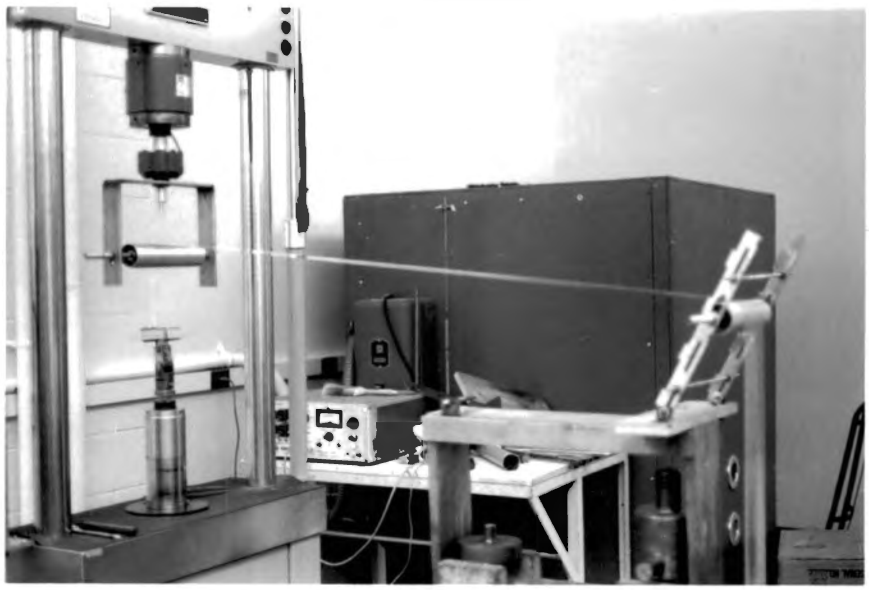


Figure 16 : Dynamic Test Equipment used with MTS Machine

TABLE IV

DYNAMIC TEST SPECIMEN SIZES AND MATERIALS

Sizes L X W	Materials
1. 7.0 ft. X 4.5 in.	Polypropylene, Aluminum foil
2. 7.0 ft. X 5.0 in.	Aluminum Coated Paper

A light source was used during the dynamic tests for the detection of the waves, their relative amplitude and the wavelength.

The dynamic tests involved testing of the following web materials: polypropylene, aluminum coated paper, aluminum foil.

CHAPTER IV

OBSERVATIONS AND RESULTS

The results of the testing of the various web materials produced information of the modulus of elasticity, yield strength, tensile strength and the elastic-plastic transition characteristics in each case of the static testing. This also provided a means for comparing the effects of the orientation on these properties of the web materials.

Static Tests

The static tests resulted in a sound knowledge base on the mechanical properties of the web materials, such as yield point behavior of the web, the directional anisotropy (MD and TD) associated with the web and the stress-strain values associated with the formation of the waves. The formation of the waves in the static mode could be associated with the tensile behavior of the web material and better explained by the stress-strain graph.

The engineering stress-strain graph, see Figure 17, for the polypropylene material is divided into three parts: the elastic region (I), elastic-plastic region (II) and the plastic region (III). Each web material (polymers, papers and metal foils) shows these three regions on the engineering

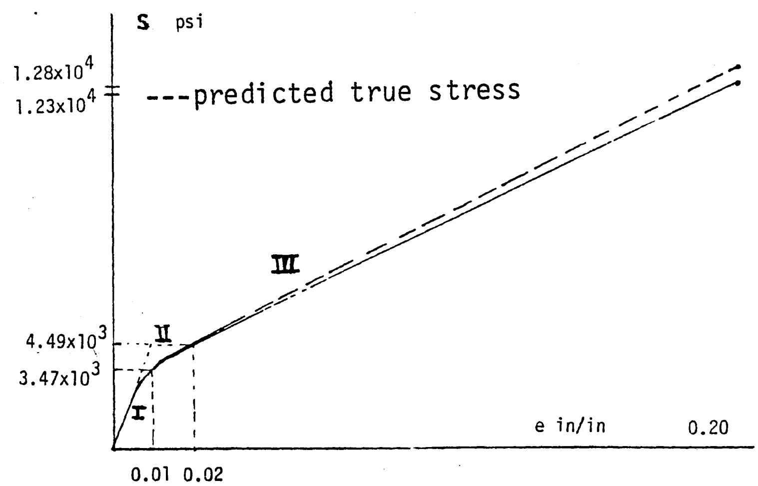


Figure 17 : Engineering Stress - Strain Diagram
for Polypropylene (MD)
Size : 7.0 X 4.5 in.

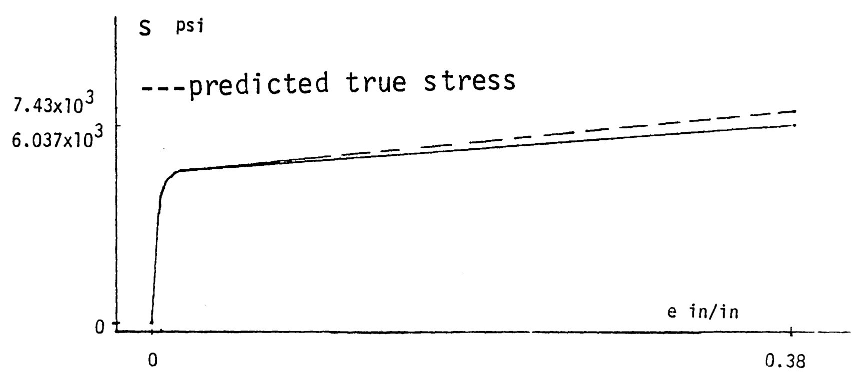


Figure 18 : Engineering Stress - Strain Diagram
for Polyethylene (MD)
Size : 8.0 X 1.0 in.

stress-strain diagram.

Elastic Region

When the material is placed in the grips and loaded, its elongation starts in a uniform manner. In the elastic region, when the material is unloaded, it returns to its original shape. In the case of metals this elastic region is quite dominant, whereas in the polymers it is very narrow and generally it cannot be distinctly marked. In polypropylene material this region occupies the initial 10% of the elongation as shown by region I in Figure 17.

Elastic-Plastic Region

As the material reaches the limit of the purely elastic response, additional loading leads to a permanent strain in the material when unloaded. Elastic spring back still occurs, but the material no longer returns to it's original dimension. This is region II on the stress-strain diagram as shown in Figure 17.

Plastic Region

In the region III, in Figure 17, the material undergoes a large strain, with a high degree of permanent deformation. Necking of the material is often observed, particularly in the thicker specimen (0.042 in. thick) in this zone. This type of deformation accounts for 85% of the total elongation in the polymers.

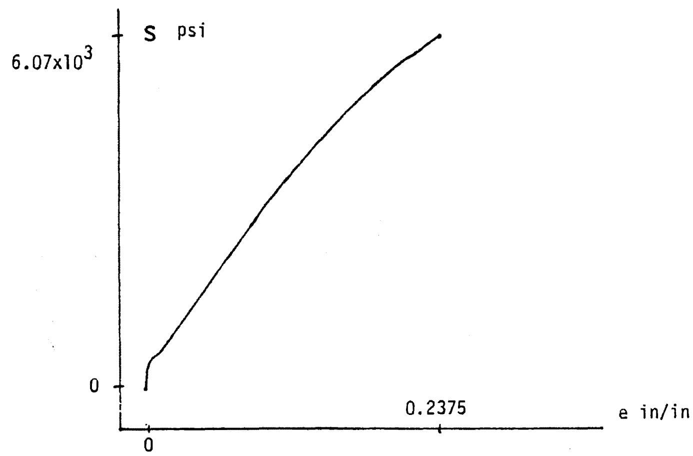


Figure 19 : Engineering Stress - Strain Diagram
of Polypropylene (TD)
Size : 4.5 X 4.5 in.

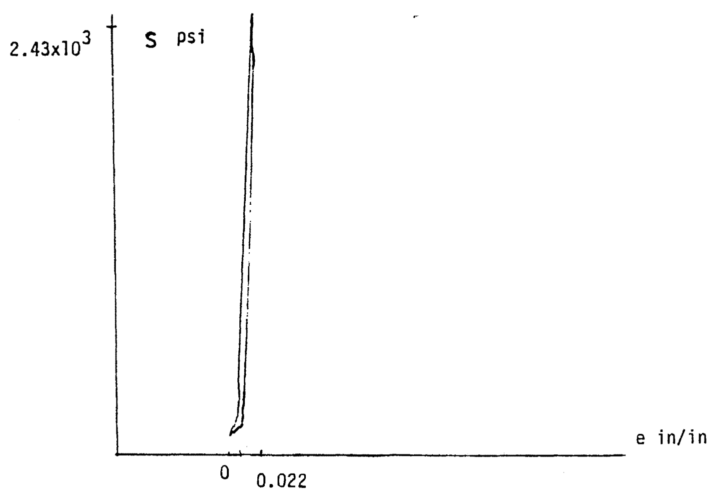


Figure 20 : Hysterisis Loop of Polypropylene (TD)
Size : 4.5 X 4.5 in.

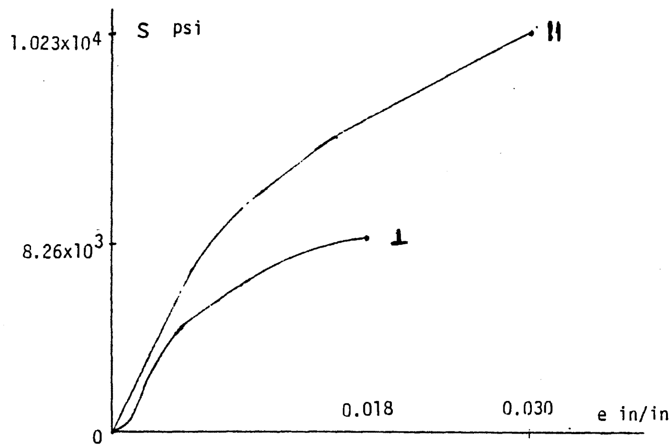


Figure 21 : Engineering Stress - Strain Diagram
of Aluminum Coated Paper
Size : 7.0 X 5.0 in. (MD)
: 5.0 X 4.0 in. (TD)

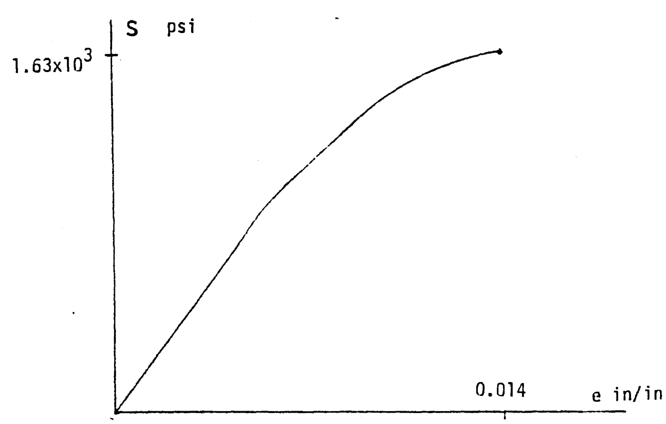


Figure 22 : Engineering Stress - Strain Diagram
of Kraft Paper (MD)
Size : 7.0 X 2.2 in.

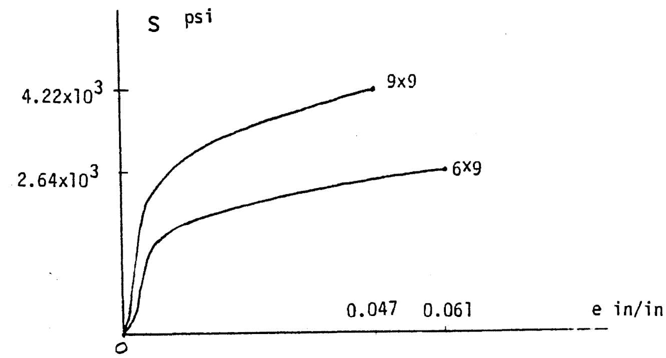


Figure 23 : Engineering Stress - Strain Diagram
of Aluminum Foil
Size : 9.0 X 9.0 in. (TD)
: 6.0 X 9.0 in. (TD)

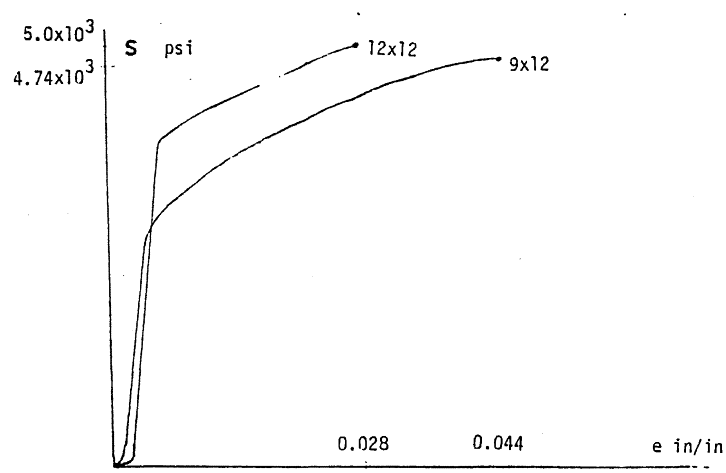


Figure 24 : Engineering Stress - Strain Diagram
of Aluminum Foil
Size:12.0 X 12.0 in. (MD)
: 9.0 X 12.0 in. (MD)

One of the important observations made during the static test of polypropylene material was, that when the test specimen was loaded in tension, it lead to wave initiation at the center of the sample. These waves then spread out as the tension was increased as shown in Figure 25. It was observed that these waves were initiated at 3650 psi, after the necking down of the polypropylene film occured. The unloading of the sample at this stage indicated a buckling type of permanent wrinkles. Two type of waves were observed, one after the necking down and the other after relaxation. The waves produced after necking could be explained with the help of the anisotropy of the material and waves after relaxation could be justified by the buckling solution.

The polypropylene, polyethylene, aluminum foil, aluminum coated paper and kraft paper were tested in the static mode and their anisotropic properties in MD and TD were evaluated. These properties alongwith the observations made are given in Tables V and VI.

It should be noted that the paper materials tested do not show any wrinkling during the loading or unloading of the sample. No wave initiation was observed the for thin or thick paper films, for these geometries and loads.

The material is said to be isotropic when the material properties are identical or uniform throughout the sample and are independant of the direction of testing. The material is reffered to as an anisotropic material when its properties differ in any one direction of testing i.e. the material

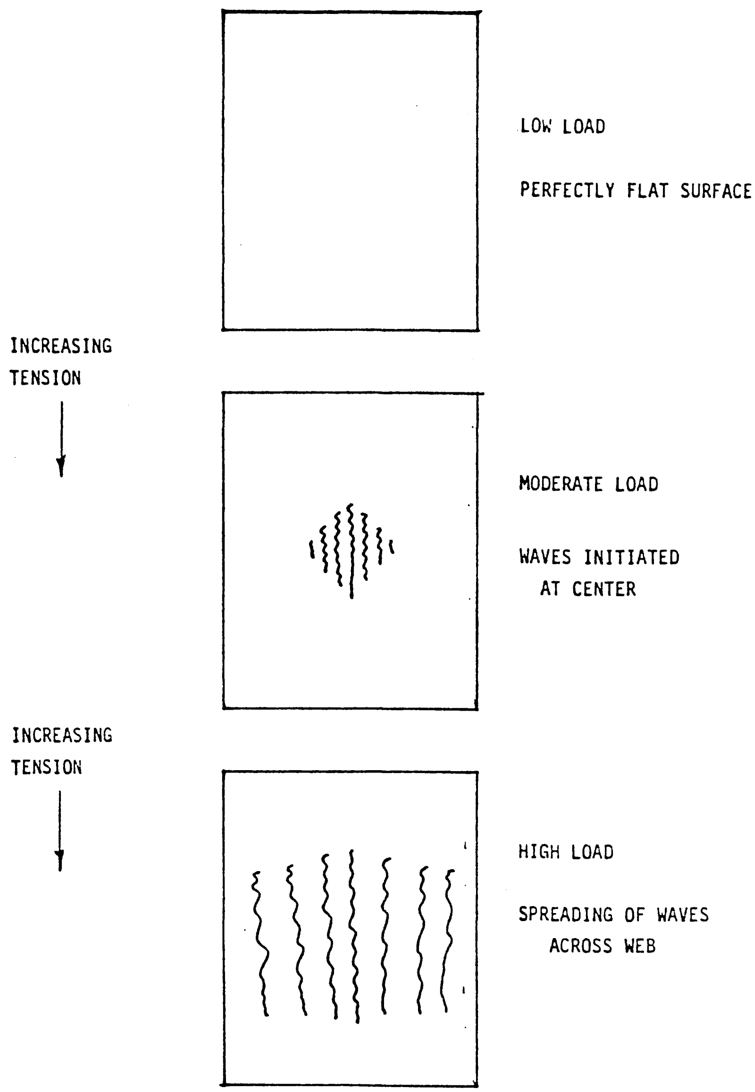


Figure 25 : Static Test Behavior of Polypropylene and Aluminum Foil

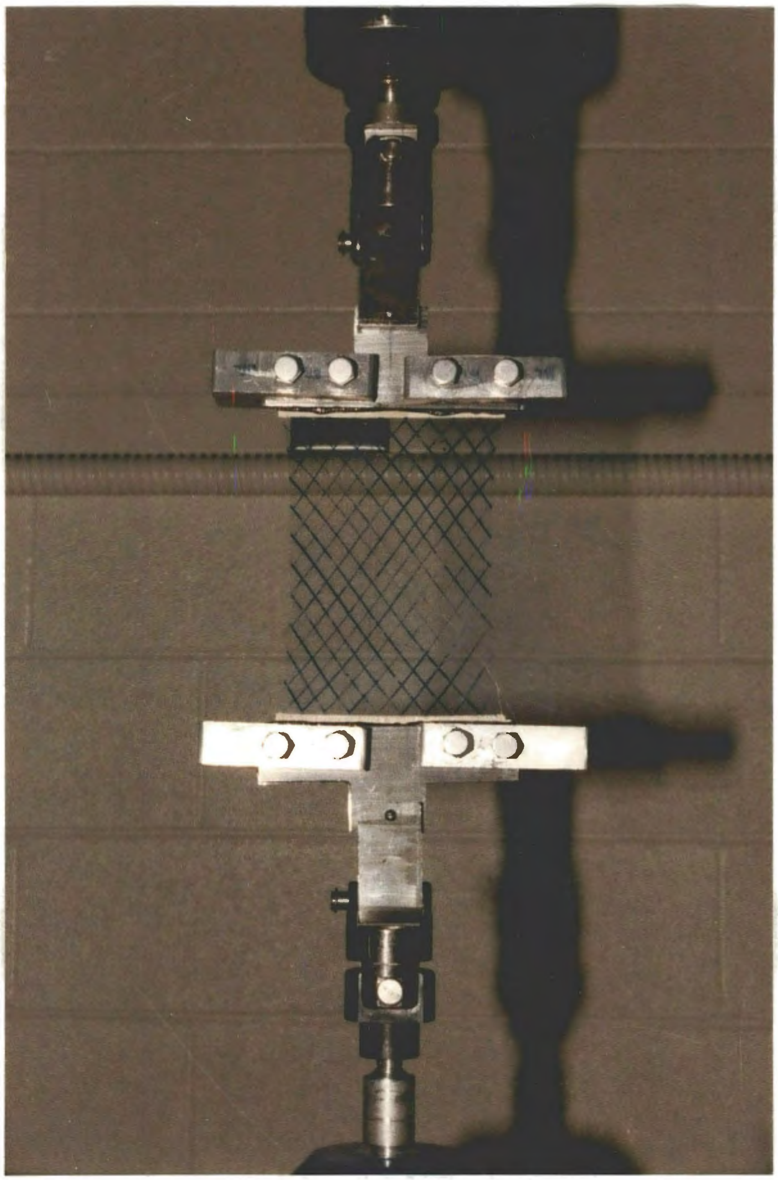


Figure 26 : Necking Effect in Polypropylene Sample

shows different directional properties. All the materials are anisotropic but the degree of anisotropy differs from material to material and from the process of manufacturing, as discussed earlier. The polypropylene material was tested in the direction of the rolling and in the direction perpendicular to rolling. From Tables V and VI it is clear that the polypropylene material has a high degree of anisotropy in MD and TD. The variation in the property is about 70% for the Young's modulus of elasticity i.e. E (TD) = 0.7 E (MD).

From the data it can be observed that the polypropylene drawn material shows about 30% variation in the tensile strength in MD and TD. The lower tensile strength (10500 psi) in TD can be easily explained. During the drawing process, the grain growth and the moleculer structure gets oriented in the direction of drawing. This directional structure leads to a poor tensile strength in the transverse direction. As the tensile load is applied to the sample in the direction perpendicular to rolling, the tear initiates at the edge of the sample and propogates along these oriented molecular chains giving a shear failure of the sample. Along with this lower tensile strength, a lower modulus of elasticity (247000 psi) is also observed. This indicates that the slope of the stress-strain curve is lower in the TD. This lower modulus of elasticity leads to longer elastic-plastic zone leading to more relaxation of the material in the direction perpendicular to rolling during the rolling process.

TABLE V

STATIC TEST EXPERIMENTAL DATA FOR LONGITUDINAL TESTS

MATERIAL	SPECIMEN SIZE L X W in	TENSILE STRENGTH psi	MODULUS OF ELASTICITY psi	COMMENTS
Polypropylene (Thick)	10.0 x 1.0	5.54 E +04	2.738 E +05	Color variations from Clear to Milky at Neck; No Waves
	8.0 x 1.0	1.01 E +05	2.276 E +05	Same
Polypropylene (Thin)	9.0 x 1.0	2.98 E +04	8.176 E +05	Shear Failure No Necking
	7.0 x 4.5	1.23 E +04	4.350 E +05	Color Clear; Necking and Wave Initiation at the Center Double Shear Failure Observed
Polyethylene	8.0 x 1.0	5.59 E +03	2.355 E +04	Large Elongation; Variations from Clear to Milky at Neck; No Waves
Paper	7.0 x 2.1	1.79 E +03	1.79 E +05	No Necking Tearing of paper Occured No Waves

TABLE V (CONTINUED)

Aluminum Coated Paper	7.0 x 5.0	1.03 E +04	3.34 E +05	No Necking Tearing of Paper Observed No Waves
Aluminum Foils	12.0 x 12.0	5.01 E +03	1.81 E +05	Initiation of Waves in the Center Spread Out as the Test Proceeded and # of waves Increased without Increasing Amplitude
	9.0 x 12.0	4.73 E +03	1.07 E +05	No Waves Flat Tearing Failure
	6.0 x 12.0	4.77 E +03	9.29 E +04	Same

TABLE VI

STATIC TEST EXPERIMENTAL DATA FOR TRANSVERSE TESTS

MATERIAL	SPECIMEN SIZE L X W in	TENSILE STRENGTH psi	MODULUS OF ELASTICITY psi	COMMENTS
Polypropylene	10.0 x 1.0	—	—	Color Variation from Clear to Milky at Neck No Waves
	8.0 x 1.0	—	—	Same
Polypropelene (Thin)	4.5 x 4.5	1.30 E +04	2.47 E +05	Necking and Wave Generation with Fewer Waves as compared to Longitudinal Shear Failure
Aluminum Coated Paper	5.0 x 4.0	7.68 E +03	1.68 E +05	No Waves No Necking Tearing Failure
Aluminum Foil	6.0 x 12.0	4.22 E +03	4.80 E +04	No Waves Generated
	9.0 x 12.0	4.58 E +03	1.05 E +05	No Waves
	6.0 X 9.0	2.61 E +03	4.35 E +04	Waves Initiated in the Center of Web and Spread Out
	9.0 x 9.0	4.22 E +03	8.93 E +04	Same

Dynamic Tests

The dynamic tests performed on the polymeric materials, metal foils and the paper materials were associated with the speed and tension effects on these materials. The results obtained from these tests provided a means of comparing the dynamic effects on the material properties with those of static effects. Also a valuable data base is obtained on the number of wrinkles formed w.r.t. the tension in the web and the speed of the web. The samples were loaded from 1 lb. to 20 lb. in tension and the speeds were varied from 32 in./min. 72 in./min.

During the dynamic tests observations were made of the web in the span between the grip and the roller connected to the load cell, the span between the two rollers and the span between the load end grip and the second roller as shown in Figures 27, 28 and 29.

The polypropylene material in the dynamic mode resulted in a variety of data related to the number of waves and the speed or tension in the web and the number of wrinkles and the speed or tension in the web. As the load of 10 lb. was applied, wrinkles were generated in the span of the grip and the roller connected to the load cell. These wrinkles when passed over this roller were spread out.

Table VII gives the details about the speeds and the tensions in the web with their relative effect on the individual materials. Figures 30 and 31 also gives a pictorial view of the effects. It is clear from the Table VII

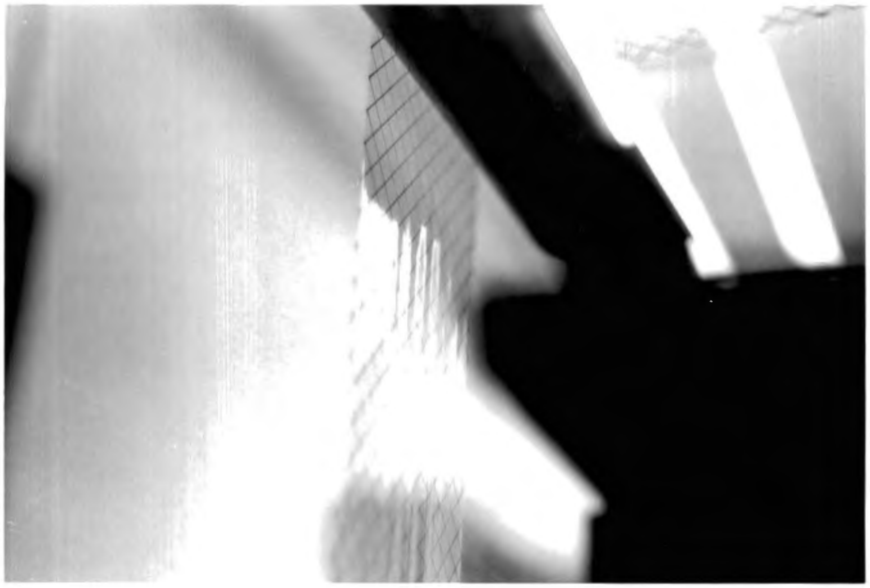


Figure 27 : Vertical Web at Loaded End

Figure 28 : Waves in Central Span of Web

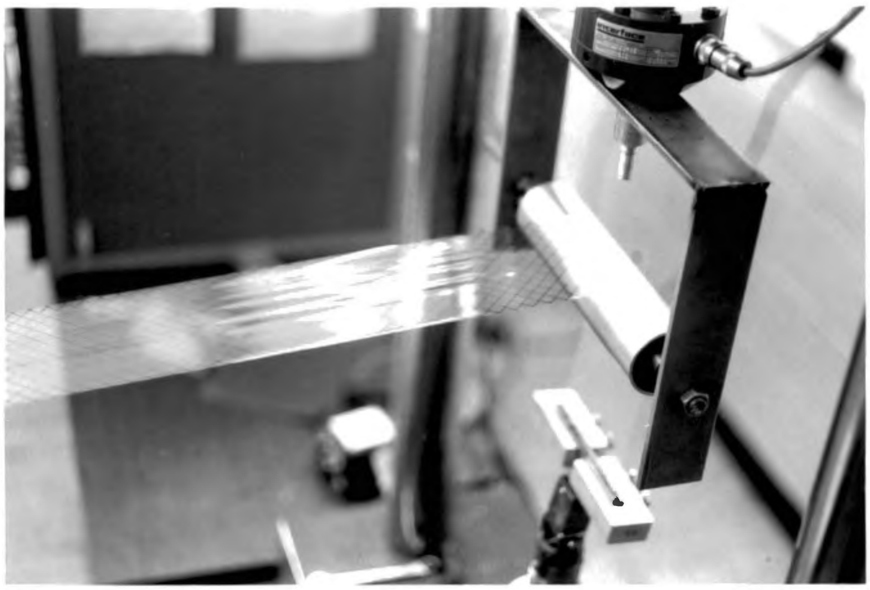


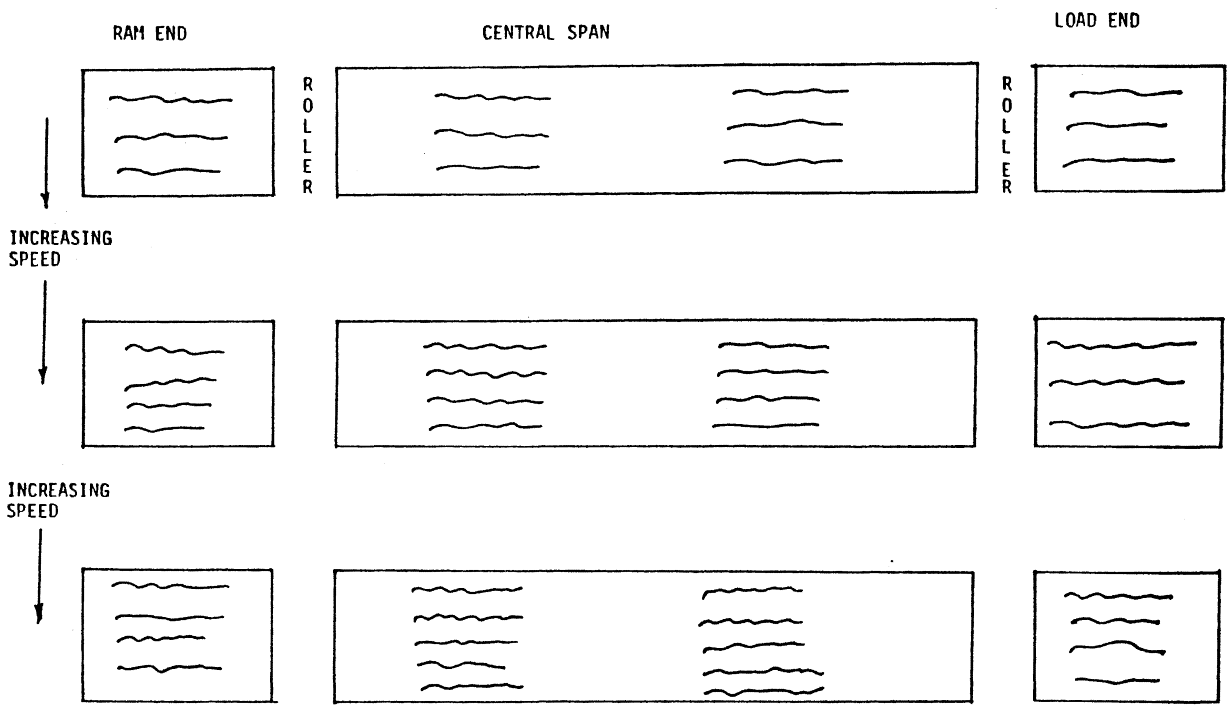
Figure 29 : Web at Load Cell End of Central Span

TABLE VII

DYNAMIC TEST EXPERIMENTAL DATA

MATERIAL	SPEED in/min	LOAD and STRESS lb & lb/sq. in.	OBSERVATION and COMMENTS
Polypropylene	36.0	1 lb & 153 psi	As the speed of the ram was increased, waves were initiated in the central span and increased in no. in accordance with the speed; but these waves were not permanent.
	40.0	5 lb & 766 psi	
	51.4	10 lb & 1532 psi	
	72.0	15 lb & 2299 psi	
		20 lb & 3065 psi	
			As the tension in web was increased the wrinkles were generated at the ram grip end and passed over the roller. These wrinkles were partially permanent.
Aluminum coated Paper	36.0	1 lb & 13.7 psi	No wrinkling instability was observed but when ram direction was altered, a surge wave was generated which disappeared after stabilization.
	40.0	5 lb & 69 psi	
	51.4	10 lb & 137 psi	
	72.0	15 lb & 207 psi	
		20 lb & 276 psi	
Aluminum foil	36.0	1 lb & 93 psi	Aluminum foils show almost same nature as that of Polypropelene except that speed increases number of wrinkles produced and both speed and tension produce permanent wrinkles.
	40.0	5 lb & 463 psi	
	51.4	10 lb & 926 psi	
	72.0	15 lb & 1369 psi	
		20 lb & 1852 psi	

*Waves are troughs midspan
Wrinkles are waves that cross rollers.



WAVES WERE NOT PERMANENT IN MATERIAL

Figure 30. Dynamic Test - Speed Effect

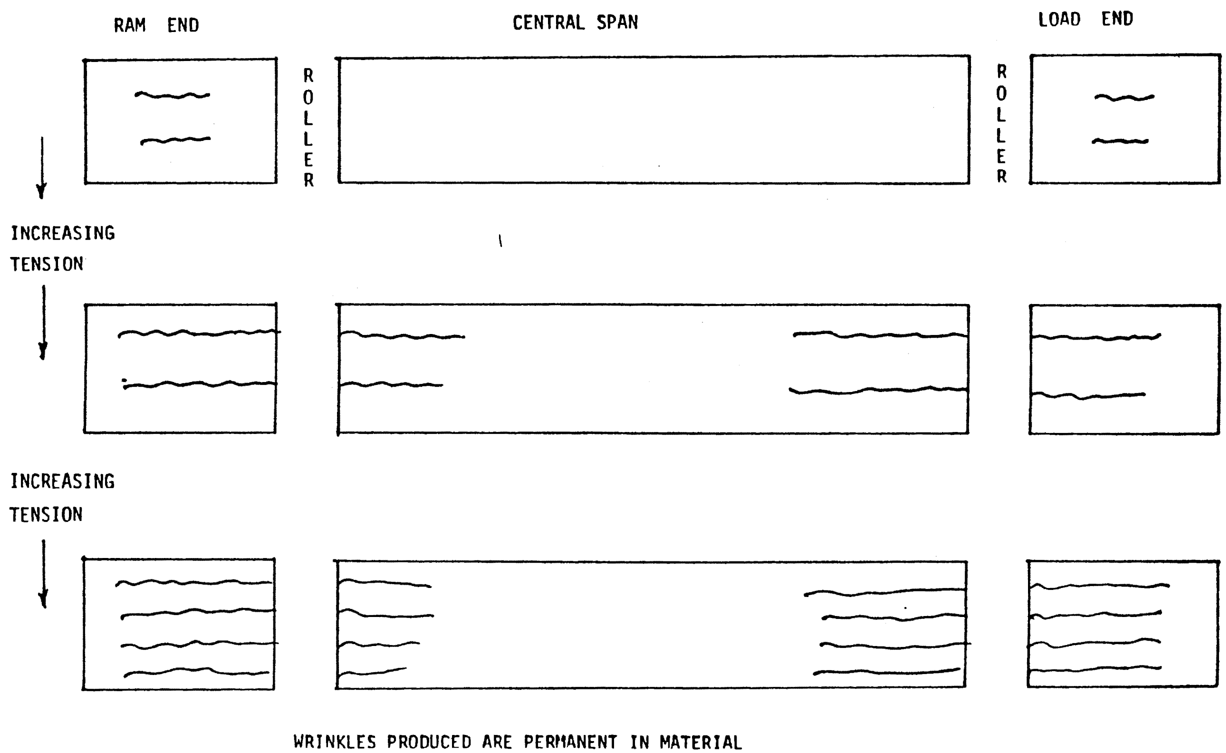


Figure 31. Dynamic Test - Tension Effect

as the speed of the polymeric web increases for the uniform loading condition of 10 lb., the number of waves generated also increase and as the speed of the web reduces for the same loading condition the waves reduce in number these waves are not permanent in the web material. The load variations were considered for the speed of 40 in./min., as the tension in the web increases the number of waves generated also increase, and as the load reduces from 20 lb. to 10 lb. the number of waves generated donot reduce i.e. the wrinkles produced due to the load variation are mostly permanent in nature with some wrinkles being temperary.

These static and dynamic test observations were helpful in the computer simulation of these cases and were correlated to the results obtained by the computer simulation. With the help of these tests the wrinkling behavior is also explained.

CHAPTER V

COMPUTER MODELING

The experimental analysis resulted in a data base indicating the possible relationship between the wrinkling instability and the effects of different variables such as the material of the web, geometry of the web sample, elastic anisotropy of the web, thickness variations in the web material, out of plane deformations, aspect ratio and the stress distribution in the web sample. The finite element (FEM) computer model was developed to further investigate the effects of these variables on the wrinkling instability.

The FEM analysis is used for analysing the web behavior in the static and dynamic modes. FEM is used for the nodal and elemental analysis and results in the stress-strain data on the elemental basis. This FEM is easily applicable to the 2-D and the 3-D models. The 2-D model uses the area elements with thickness incorporated in them, whereas the 3-D model considers the volume elements for the evaluation of the problem. The 2-D model does not consider the thickness variation effect while the 3-D model is capable of evaluation of the thickness changes associated with the model. Also with the FEM approach once the code is developed for the geometry in consideration, minor changes in the code result in the evaluation of the variables such as the material anisotropy, aspect ratio and material properties. Also different boundary conditions could be applied to simulate the different types of cases related to the web processing.

The NASTRAN software package developed by NASA for structural analysis was used on the International Business Machine (IBM 3081k) computer. NASTRAN has the capability of incorporating the anisotropic properties of the material within the elastic region. This software was used to perform the static and dynamic analysis simulation (10).

NASTRAN does not determine the material behavior in the permanent deformation region i.e. plastic region. Therefore, the computer modeling is limited in terms of material behavior, to the elastic deformations, identifying those areas that are surpassing the elastic limits into the plastic region.

The following two types of models were developed using NASTRAN; a 2-D model of single plane of elements as seen in Figure 32, and a 3-D model with multiple elements through the thickness as seen in Figure 34.

Static Test Model

The static test model was developed using displacement boundary conditions and it is a simulation of the static test performed on the MTS machine for the tensile properties of polymeric materials and aluminum foils. The Figure 32 shows the static test model used with the boundary conditions imposed on the model. The nodes of the model on one end were constrained to permit zero displacement in any direction representing the experimental tests where the specimen is fixed at one end in the grips without any possible motion. A fixed displacement, using single point constraint was imposed on the nodes of the other end of the model constraining these nodes to motion in the direction of pulling only. By using these displacement boundary conditions, see APPENDIX C for complete code setup, the deformation pattern and stress distribution pattern were observed.

2-D Model

The static modeling of the tensile tests were involved with the samples tested on the MTS machine. These samples were of two sizes; thin samples 0.00143 in. thick and thick samples 0.042 in. thick. During the experimental analysis it was observed that the thin samples necked down without any thickness reduction (within 2%) while the thick samples necked down with an observable thickness reduction.

Due to these experimental observations a 2-D model was developed to simulate the thin samples with the displacement boundary conditions as discussed above. Due to the tensile loading developed by these boundary conditions the center region of the sample necks down as shown in Figure 32. This necking down effect is symmetrical about the central axis and is in conjunction with the experimental observations.

The stress values and the stress contors associated with

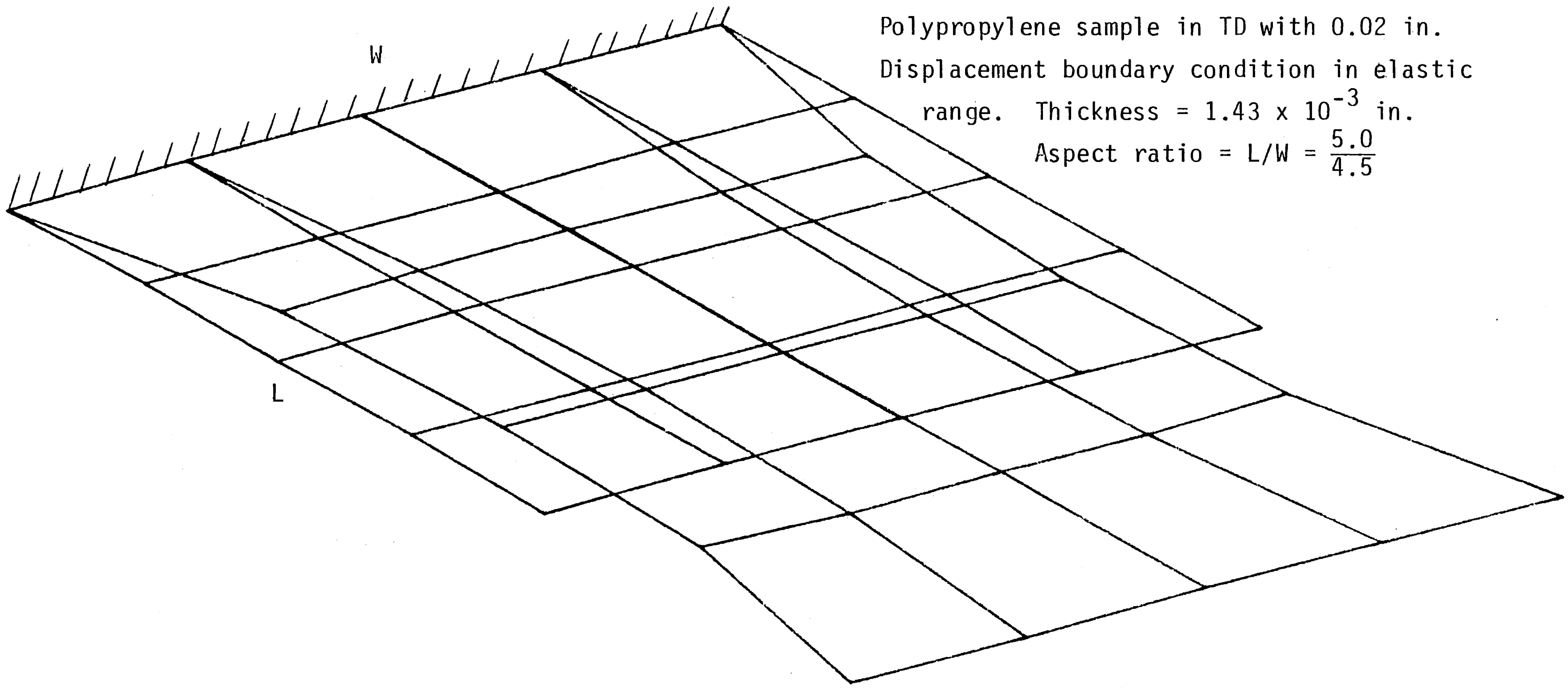


Figure 32. Undeformed and Deformed Shape of Static Test Model: 2-D Analysis

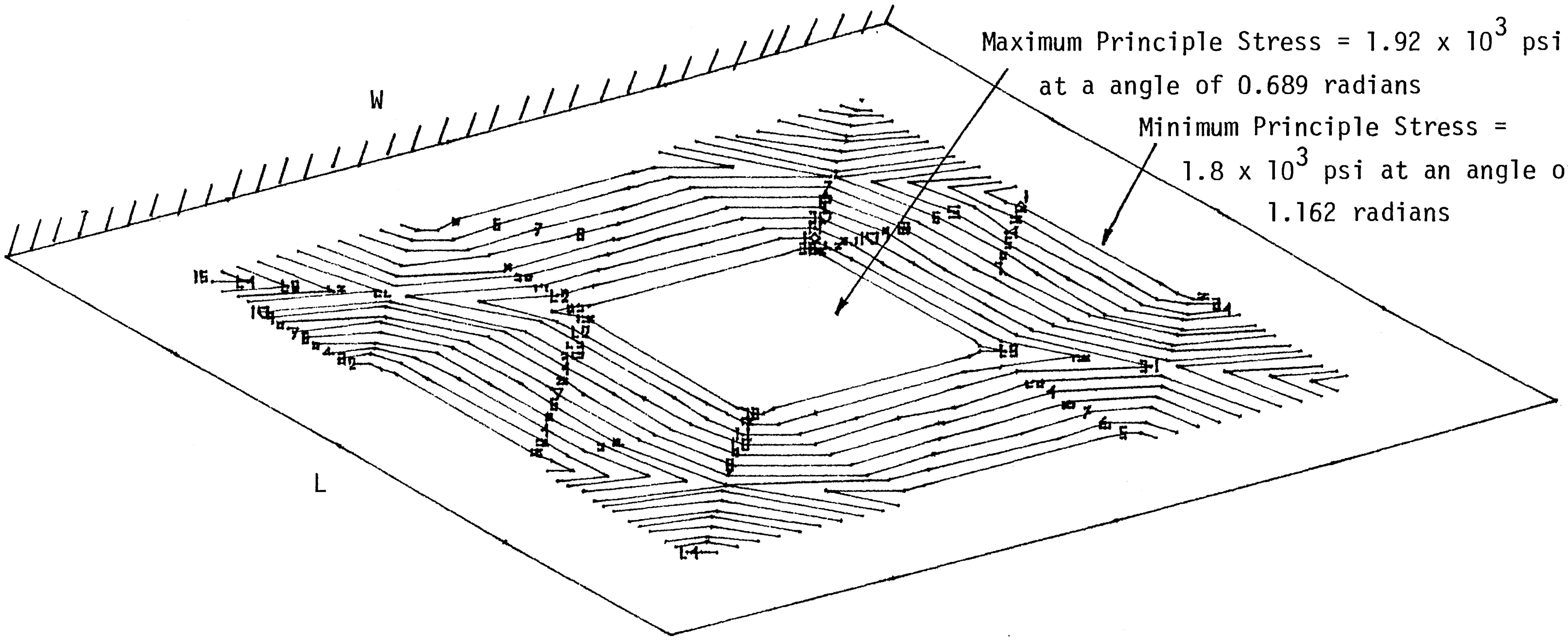


Figure 33. Maximum Principle Stress Contour Plot of Static Test Model: 2-D Analysis

this model are as shown in Figure 33. These are the stress contors obtained on the undeformed shape of the sample for better understanding of the variation in the stresses after the tensile loading is applied. The stress variation of about 10% is observed from the edge of the sample to the center of the sample.

This 2-D model was used with the material properties obtained from the experimental analysis for the polypropylene film and for the aluminum foil. The material properties that were involved with this static 2-D simulation were the Modulus of Elasticity, poisson's ratio and the density of the material. The Modulus of Elasticity for these two materials were obtained with the experimental tests performed on these materials. Also material anisotropy was incorporated for better understanding of the web material behavior. A thick (0.042 in. thick) sample tested experimentally was modeled using 3-D volume elements.

3-D Model

To get a clear understanding of the thickness effect a 3-D model was developed with displacement boundary conditions as discussed before. The three different sample thickness (0.00143 in., 0.042 in., 0.084 in.) were analysed with the computer model. The deformation plot is shown in Figure 34. It was observed that the thickness variation associated with the thin sample (0.00143 in.), is negligible (less than 5%) indicating that the earlier assumption of using a 2-D model

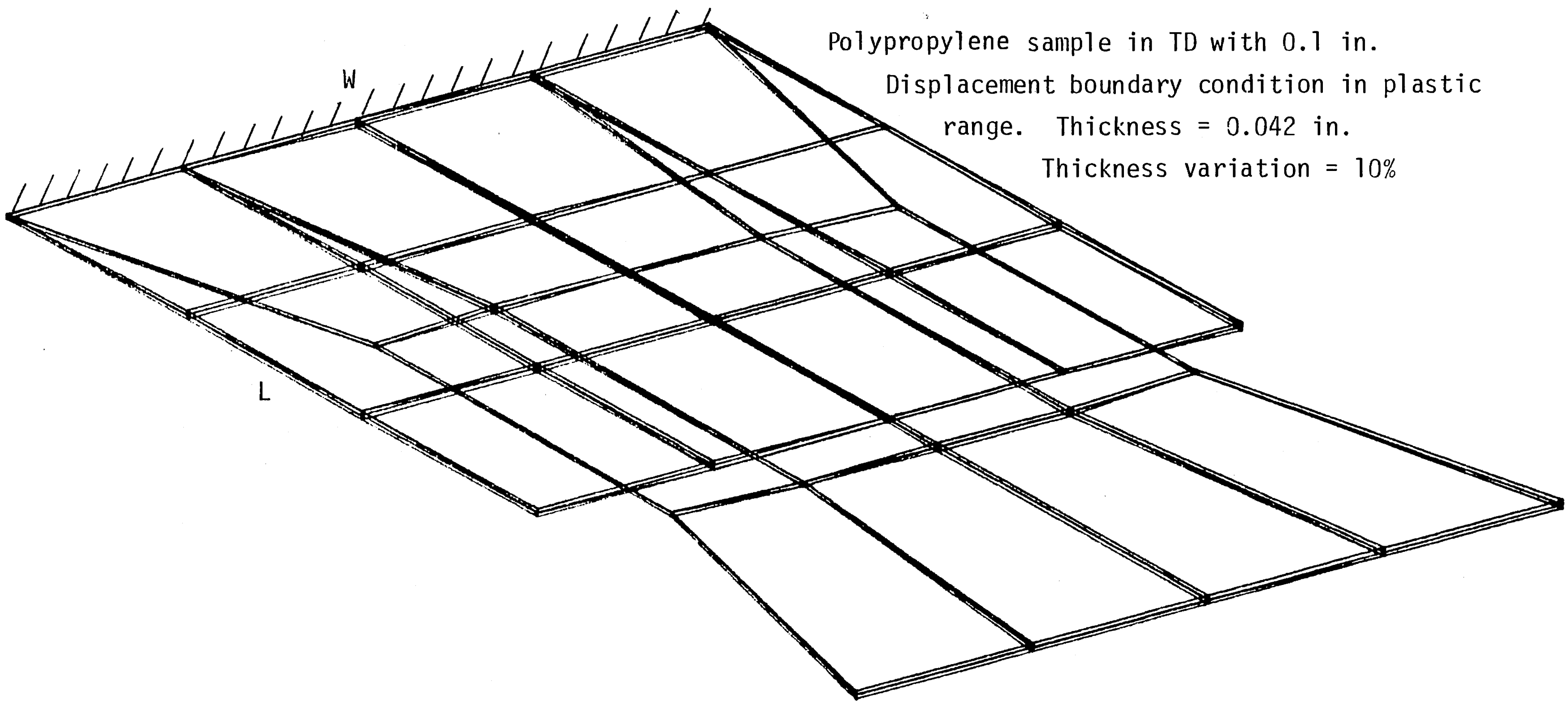


Figure 34. Undeformed and Deformed Shape of Static Test Model: 3-D Analysis

for samples 0.00143 in. thick is valid. The Figure 34 shows a necking down effect of the 3-D model which is similar to that obtained with 2-D model.

The thickness variation of about 40% was observed during the experimental testing of 0.042 in. thick samples. The variation in thickness along the width was also observable for these sample during testing. In the 3-D modeling of this thickness a similar thickness variation was observed in the transverse plane. It was also noted that the thickness variation in this case was non-uniform and a partly wavy nature of thickness variation was observed.

The stress distribution in the 3-D case was similar to that obtained with the 2-D model except that the stress variation was also observed across the thickness plane of the sample. The stress values associated with this model were maximum at the necked down center portion with reduction in stress along the boundaries.

Dynamic Test Model

This model was developed using the force boundary conditions and the displacement boundary conditions to simulate the dynamic tests performed on the MTS machine. The polypropylene film material (0.00143 in. thick) was used for the experimental tests and the same is modeled. As discussed earlier due to small thickness of the samples 2-D analysis was chosen throughtout the dynamic modeling.

In the case of dynamic modeling of polypropylyne web the

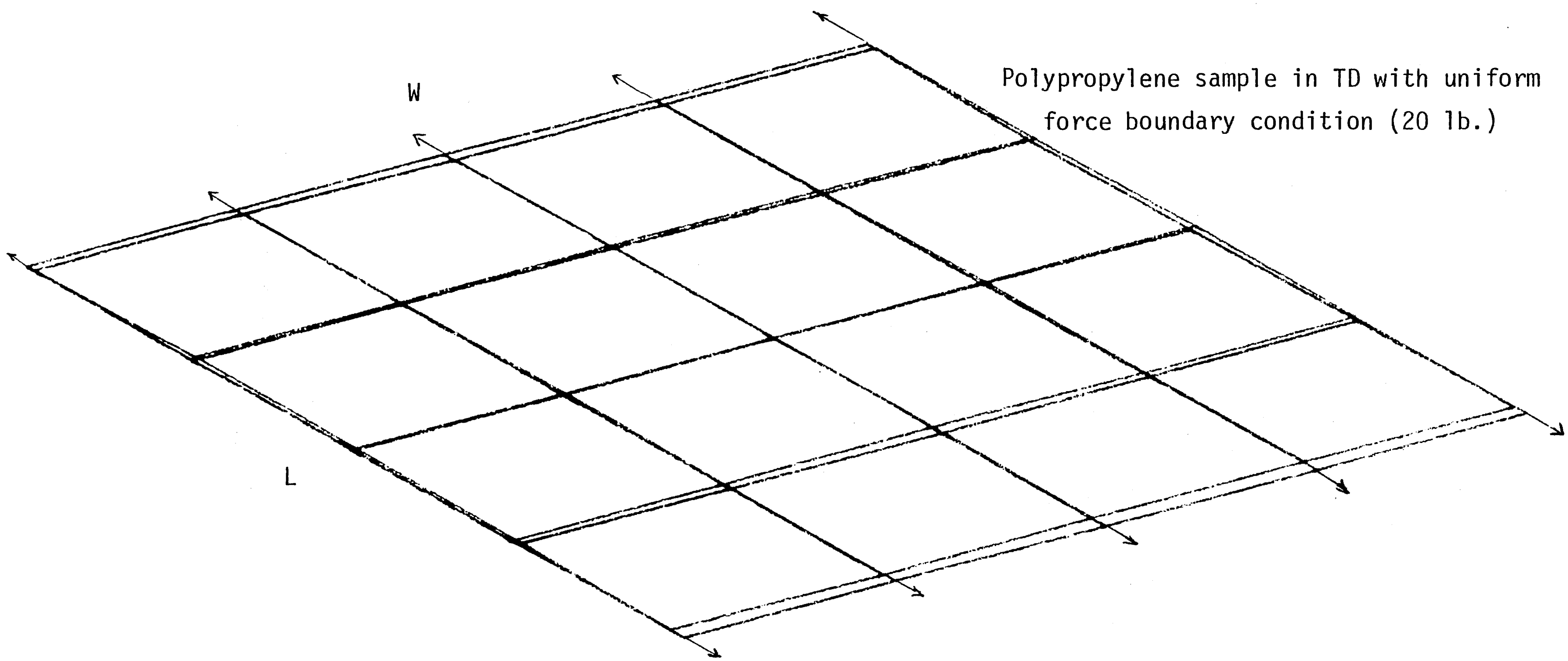


Figure 35. Undeformed and Deformed Shape of Dynamic Test Model: 2-D Analysis

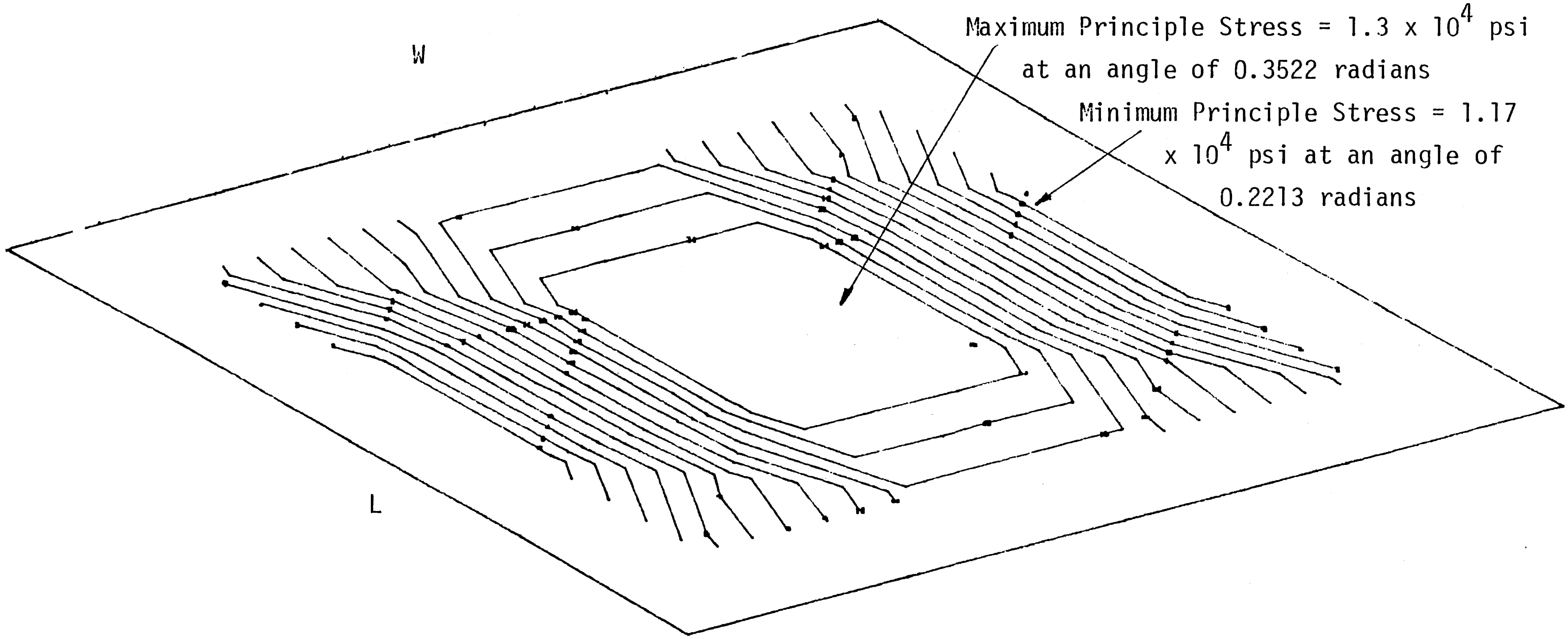


Figure 36. Maximum Principle Stress Contour Plot of Dynamic Test Model: 2-D Analysis

force boundary conditions were used. As the rubber lined grips are capable of applying a uniform force on the web in motion the uniform loading conditions were applied to the nodes on the web which were supporting this load. The web was also constraint from any rotary motion and was unconstraint in the translational motion in all the three directions. The boundary conditions applied are shown in Figure 35. The effect of the loading on the deformation of the web is also shown in Figure 35. The deformation associated with the type of loading applied though small can't be neglected due to the stress values associated with these strains.

The stress variations in the web were also observed in this model. The stress variations are similar to those observed in the static modeling of the web but the stress values are different in magnitude and are given in Figure 36. The stress is maximum at the center of the web and reduces towards edges.

For this dynamic analysis the polypropylene material was used with the properties obtained from the experimental tests performed in the static manner. The correlation of the model and the experimental analysis is obtained and is discussed in the next chapter.

Models for Rollers

Bowed roller, concave roller and inclined roller were simulated by using an approximate force boundary conditions. All the data base for these models is given in Appendix C.

CHAPTER VI

DISCUSSION AND ANALYSIS

This chapter is devoted to correlating the data obtained from computer analysis (2-D and 3-D), experimental work and material effects and the comparision of the properties with the earlier literature.

In the case of static tests performed on polypropylene material for different thicknesses (0.00143 in. i.e. thin and 0.042 in. i.e. thick) it was observed that the thin web behaves differently with respect to the thick film. The thin film shows yielding with the width reduction and the wave initiation associated with the center portion of the web. As compared with this behavior shown by the thin polypropylene films the thick film yielding shows the width reduction and the color variation from transparent to opaque white. It is also accompanied by the thickness reduction along TD but does not show any wave initiation. In both these cases i.e. thin and thick film yielding the end effects does not show any significant effect on the behavior of the web material. From these observations it is necessary to further establish the transition thickness at which the material behavior changes from the near plane strain case (thick) to the plane stress case. This thickness effect is dependant on the manufacturing process used as discussed in Chapter 2 and the material properties of different web materials.

For the polypropylene, aluminum foils tested in both MD and TD the tensile properties are non-uniform showing the anisotropic nature of the material. The polypropylene film shows the tensile strength of 12300 psi and the yield strength of 3470 psi in the machine direction (MD). This material also shows the Young's Modulus of Elasticity as 4.34 E +05 psi. In the case of isotropic material the tensile strength is 6000 psi, yield strength is 3500 psi and the Modulus of Elasticity is 2.5 E +05 psi. These values are different due to the anisotropic nature of the material produced due the tentering technique used, as discussed in Chapter 2. For the same reason the tensile strength of the polyethylene material tested is 6070 psi as compared with it's isotropic value of 4500 psi in the MD. For the kraft paper tensile strength obtained by experimental testing is 1630 psi while the isotropic value is 1000 psi.

It was also seen that there is no correlation between the s/E ratio for MD and TD. For different thicknesses this ratio leads to a range of values varing from 0.30 to 0.45 for thick (0.042in.) samples in MD and 0.13 to 0.20 in TD, and 0.02 to 0.026 for thin (0.00143 in.) samples in MD and 0.03 to 0.074 in TD. This shows that as the thickness of the sample varies there is a variation in yield point stress and modulus of elasticity ratio in both MD and TD and thus the effect of the thickness on material behavior is to be investigated.

The wave generation in the polypropylene and the aluminum foils is associated with the geomerty of the sample i.e. the apect ratio, the tensile load applied and the material response to the loading conditions. As the length of the specimen was increased keeping the width constant the wave generation was observed. Also the loading associated with the wave initiation was in the elastic-plastic zone of the material. The polypropylene and aluminum foils shows the wave initiation characteristics while the paper material does not show this property which could be associated with the poisson's ratio of the kraft paper (0.35 to 0.49).

Analysis of the static test and its model is done here. A polypropylene material of size 7.0 in. X 4.5 in. was tested experimentally and it was observed that it gives wave initiation at the center portion when pulled. A NASTRAN model for this case (2-D) shows similar necking down effect at the central span of the specimen. Also as expected it gives a high stress concentration point at the center of the sample where the sample is necked down. This can also be explained by theory of true stress-strain in engineering materials. When a sample necks down the load required to continue its elongation or further necking reduces considerably but the true stress associated with this necking is considerably high. As sample necks down, the area supporting the load reduces leading to high concentration of stresses at the necked down region as obtained from computer model and experiments test.

The elongation associated with this size model was in accordance with the elastic range of the stress-strain curve.

For the elongation of 0.02 in. i.e. engineering strain of 0.004 in/in. the stresses obtained by calculation and by model showed small variations with each other for the true stress value. Also the engineering stresses calculated from this computer analysis were compared to the experimentally obtained graph of engineering stress-strain; the model acts as an exact replica of experimental work and can be substituted for the experimental work in the elastic range.

For an elongation of 0.05 in. i.e. engineering strain of 0.01 in/in. when the engineering stresses calculated from the computer model and from experimental engineering stress and strain curve were compared, it was found that the computer model deviates from the actual experimental values. The reason for this deviation lies in the fact that for this elongation of the web material (polypropylene) stresses in the material are in the transition zone of elastic-plastic. This model can not be used to solve the problem beyond the elastic range of material. NASTRAN use should be limited for elastic portion only and a new code should be developed to model the elastic-plastic region of material.

To strengthen the above view one more deformation was modeled. When elongation given is 0.1 in. i.e. an engineering strain of 0.02 in./in., the engineering stress obtained by computer model is significantly different (50%) to the stress value obtained by experimental work.

In both the above cases (0.05 and 0.1 in. elongation) when elastic line on the curve is extended, the value of the stresses obtained matches with a very small error (5% to 12%).

Sample calculations of the above analysis are given here for a better understanding for the elongation of 0.02 in.

By calculation :

True Strain = e(t) = ln (le / lo) = ln (5.02 / 5.0)

= 0.004 in/in.

Young's Modulus of Elasticity = E = 4.35 E +05 psi.

True Stress = s(t) = E X e(t) = 1740 psi.

By computer model :

True stress = s(t) = 1900 psi.

Original Width = w = 4.5 in.

Reduced Width = w(r) = 4.49 in.

Engineering Stress = s = s(t) X w(r) / w

= 1890 psi

By experimental test :

Engineering Strain = e = (le - lo) / lo

= (5.02 -5.00) / 5.00

= 0.004 in/in.

from graph we have,

Engineering Stress = s = 1800 psi

% error calculation :

% error between calculation and NASTRAN model = 7.9%

% error between calculation and experimental test = 3.3%

% error between NASTRAN model and experiment = 4.76%

The stresses obtained by this NASTRAN model also partly reflect the reason for central wave initiation in the static model. A close look at stresses and stress contours show that the normal stresses are not uniform throughout the specimen. A higher stress value is associated with the central region of sample 1917 psi. The stresses get reduce towards the edges (1800 psi) and boundaries (1830 psi). When the sample is pulled through a certain distance it goes into the plastic region from initial elastic region. This transition is very critical. At a particular elongation the normal stresses associated with the edges or ends are in the elastic region whereas the stress values associated with central region of the specimen are in the elastic to plastic transition range forcing it to behave differently from other elements of the same sample. Also a similar case exists when the sample is further elongated. In this case the edges and ends are in the elastic-plastic transition zone while center portion is already in plastic range of material. This also leads the center region of the specimen to behave differently and gives a variable property. This phenomenon in the material sample is responsible for the variation in the properties in the different zones of the sample leading to the wave initiation in the central zone of the sample. In the experimental testing it was observed that the stress value associated with the wave initiation is about 5% after necking down of the specimen (2500 psi).

Now we will consider the a 3-D model of same size and thickness (0.00143 in.). This 3-D model doesnot show a large thickness variation in the sample, and the results obtained are similar to a 2-D model. From this analysis it may be concluded that for thin web samples 2-D model serves as a good approximation. Also for such a thin sample the material acts as a plane stress case and has almost zero deformation in thickness plane. This was also clear from MTS machine static tests as no thickness variation was observed for thin samples.

For the thicker models (0.042 in. or 0.084 in.) a 3-D approximation is closer to reality. Especially with a thick sample like 0.042 in. a significant thickness change is observed in the model and in the experiments. For this thick a specimen material no longer behaves as a plane stress case but tends towards a near plane strain case. In other words the in plane and out of plane deformations can no longer be neglected and the poisson's effect should be considered. This was clearly seen by naked eyes during the static tests performed. Due to poor stiffness of the thin samples the waves are dominant as compared with the thick sample.

Waves in the thin sample could also be associated with anisotropy of polymer. As mention earlier in the experimental chapter polypropylene has a large anisotropy involved in the machine direction (MD) and transverse direction (TD). Young's modulus of elasticity in these two directions differ in value by about 30%, MD has a higher modulus value than TD. This variation in the E value is associated with manufacturing and orientation process, due to alignment of the crystals in the direction of rolling. As E (TD) is lower, the stress value associated with the yielding in this direction is also lower as compared to one in the machine direction by about 40%. This leads to an unusual phenomenon of elastic-plastic transition leading to wave initiation as explained earlier.

In the case of isotropic material (Appendix C) the stress variations shown by the model though are similar in nature the variation in the stresses is about 2% which is significantly lower than that for the anisotropic material. Also due to higher yield point associated with the isotropic material in the TD the probability of wave initiation is less and due to higher Modulus of Elasticity value in TD the range of the elastic limit is increased and the elastic-plastic transition is delayed. Also in the case of aluminum foils due to lower modulus of elasticity the stresses associated with the center portion of the model are lower (25%) than that obtained with polypropylene material.

Dynamic test analysis involved the study of the effect of speed and tensile loading on the material. The spreading effect of the rollers was also observed during these dynamic tests performed on the polypropylene and the aluminum foils. This effect was not observed in aluminum coated paper.

For the case of increasing tension the wave generation and wrinkle formation could be explained by elastic-plastic region. When the tension starts exceeding the elastic zone in the transverse plane wave initiation starts and therefore leads to permanent wrinkles that cannot be spread out.

CHAPTER VII

CONCLUSION

The extensive experimental study coupled with computer modeling resulted in a sound data base for the future researchers. Some of the important conclusions were drawn with the help of this study and should be a basis for further research in this area and these are given below :

Thin film material definitely plays a major role in the initiation of waves, progressively changing into wrinkles. The polymers and aluminum foils below a certain thickness show this phenomenon but paper material does not behave in a similar manner.

The web thickness appears to affects the wave generation characteristics, and there is a critical thickness at which the material response varies from near plane strain behavior in thicker films to a plane stress case in thin films. The thick material (0.042 in. thick) does not produce any waves. The thin film (0.00143 in. thick) materials produce waves which may progress to the formation of the wrinkles. The polymers and the aluminum foils exhibited this behavior for the thinner films tested. The paper material tested does not show any wave initiation or wrinkling characteristic.

Polymeric materials and aluminum foils do show a significant variation in the properties in longitudinal and transverse directions leading to poor directional properties.

Since the stiffness of the material in the transverse direction is less than that in longitudinal direction; it tends to give a buckling effect in the transverse plane.

Elastic, elastic-plastic and plastic characteristics of the material have a profound effect on the web behavior in different stages of the process. The transition from elastic to plastic zone has been studied in great depth showing that in this region the material exhibits characteristics of wave generation. Also the material during the tensile loading shows the stress variations leading the material to behave differently in the different regions resulting in the wave initiation in the center portion of the sample.

In the dynamic process, the speed of rolling and the tension in the web affects thin polypropylene and aluminum foil in almost the same manner. Increasing speed produces waves and number of waves generated are directly proportional to the speed. Increasing tension produces waves which later turn into wrinkles.

Recommendations for Future Research

1. There is a need to examine webs of various thicknesses to obtain those values of the thickness of web at which the material changes its behavior from the near plane strain case to the plane stress case.
2. Dynamic tests should be performed with different materials

and different thicknesses at higher speed to get a true measure of speed effect.

3. Temperature effects on the polymeric materials are very critical and need to be investigated throughly.
4. A study of the effect of the web material response to the different roller materials should be done.
5. The effect of the tentering operation in terms of the tension, temperature and the time effects upon the stress relaxation and the wrinkling instability in web should be investigated.

SELECTED BIBLIOGRAPHY

1. Good, K. and Papandreadis A. The development of finite element modeling techniques of web and the analysis of web wrinkle formation, July 1986.

2. Briston J. H. Plastic Films, Manufacturing methods, ch. 8, 63-79, and Appendix A, Properties of Plastic Films, 287.

3. Rigby H. A. Production, Properties and Packaging Applications of Polypropylene, ch. 3, 56-150.

4. Park W. R. R. Plastic Film Technology, Methods of manufacture, ch.2, 10-45, Physical properties of plastic films, ch. 4, 123-143.

5. Ladbury J. W. Production, Properties and Packaging Applications of Polyethylene, ch. 2, 24-34.

6. Griff A. L. Plastic Extrusion Technology, Film, ch. 5, 87-105.

7. Training seminar on Paper Making, Web Handling Research Center, Oklahoma State University, Stillwater, Ok.

8. ASTM testing handbook, 1985, Tensile Properties of Thin Plastic Sheeting, D882-81, Vol. 8.01, 471-480.

9. ASTM testing handbook, 1985, Tension Testing of Metallic Foil, E345-81, Vol. 3.01, 519-523.

10. Martin A. G. Calculation of elastic properties of anisotropic sheets and rods of cubic and hexagonal crystals, Army Materials and Mechanics Research Center, AMMRC TR 71-15, July 1971.

11. National Aeronautics and Space Administration, NASTRAN User's Manual, Washington D. C. : U. S. Government Printing Office, 1984.

12. Duffin D. J. Laminated Plastics, 2nd edition, Manufacturing processes, ch. 4, 59-67.

13. Hoyt S. L. Metal Properties, 341.

14. Modern Plastics Encyclopedia, 1985-86, 52-60, 77-78, 468-475.

15. ASM Metals Handbook, 1978, Vol. 1, 357-379.

16. ASM Metals Handbook, 1978, Vol. 2, 64-68.

17. Structural Alloys Handbook, 1973, Vol. 2, Wrought Aluminum Selector Chart, 1-5.

18. Aluminum Foil in Packaging, Symposium proceedings, 1968, Aluminum Federation, How to select flexible foil packaging laminate, 16-23.

19. Shelton, J. J. and K. N. Reid. Lateral dynamics of an idealised moving web. Journal of Dynamic Systems, Measurement, and Control, Sept. 1971, 187-192.

20. Shelton, J. J. and K. N. Reid. Lateral dynamics of a real moving web. Transactions of ASME, Sept. 1971, 180-186.

21. Tsai-Soong and Chun Li. An elastic analysis of multiroll endless web systems. Transactions of ASME, Dec. 1979, 101, 308-313.

22. Daly D. A. Factors controlling traction between webs and their carring rolls. Tappi, Sept. 1965, Vol. 48, No. 9, 88 A-90 A.

23. Frye Kenneth G. Winding variables and their effect on roll hardness and roll quality. Tappi, July 1967, Vol. 50, No. 7, 81 A-86 A.

APPENDIXES

APPENDIX A

EXPERIMENTAL RESULTS

Experimental data is presented here for the static test performed on MTS machine.

Sample Calculation

Here the method of calculating engineering stress, true stress, engineering strain is given.

$$\text{Engineering stress} = s = \frac{\text{load applied}}{\text{area}}$$

$$\text{True stress} = s(t) = \frac{\text{instantaneous load}}{\text{area}}$$

Load applied can be directly obtained from the load cell of the MTS machine. This load obtained is multiplied by a scaling factor for load cell (22.54 for 500 lb. load cell used for these experiments).

Load applied = Digital reading X 22.54 lb.

Area supporting load = A = Width of specimen X Thickness

A = w x t sq. in.

For calculating engineering stress,

w = original width

t = original thickness.

For calculating true stress

w = instantaneous width

t = instantaneous thickness

For sample # 1, we have

$$s = \frac{\text{load} \times 22.54}{w \times t}$$

To get the true stress at fracture we have

$$s(t) = \frac{\text{inst. load} \times 22.54}{w \times t}$$

Calculation of engineering strain is as shown below,

$$\text{Engineering strain} = e = \frac{\text{Change in Length}}{\text{Original length}}$$

$$= \frac{L\ (\text{final}) - L\ (\text{original})}{L\ (\text{original})}$$

$$=$$

$$\text{Modulus of Elasticity} = E = \frac{\text{stress in elastic region}}{\text{corresponding strain}}$$

$$E = \frac{s}{e}$$

TABLE VIII

TENSILE PROPERTIES OF POLYPROPYLENE IN LONGITUDINAL DIRECTION

No.	SIZE 1 X w in.	ENGINEERING YIELD STRAIN in/in.	TENSILE STRENGTH psi E +04	YIELD STRENGTH psi E +04	MODULUS OF ELASTICITY psi E +05
Thickness : 0.042 in.					
1.	10.0 X 1	0.0168	5.540	4.599	2.738
2.	8.0 X 1.0	0.0370	10.12	8.421	2.276
3.	8.0 X 1.0	0.0377	8.850	7.366	1.954
4.	8.0 X 1.0	0.0257	4.990	4.147	1.614
Thickness : 1.43 E -03 in.					
1.	9.0 x 1.0	0.01467	2.998	1.199	8.17
2.	8.0 X 1.0	0.01876	3.146	1.258	6.70
3.	8.0 X 4.5	0.00600	0.688	0.275	4.55
4.	7.0 X 4.5	0.00800	1.230	0.347	4.34
5.	7.0 X 4.5	0.01128	1.230	0.492	4.35
6.	7.0 X 4.5	0.00980	1.656	0.662	6.75
7.	7.0 X 4.5	0.00940	1.167	0.467	4.97
8.	7.0 X 4.5	0.00984	1.032	0.413	4.18
9.	7.0 X 4.5	0.00940	0.916	0.366	3.88
10.	7.0 X 4.5	0.00820	1.341	0.536	5.90
11.	7.0 X 4.5	0.01032	0.933	0.373	3.61
12.	7.0 X 4.5	0.00918	1.788	0.715	7.82
13.	7.0 X 4.5	0.00944	1.544	0.618	6.52
14.	7.0 X 4.5	0.00952	1.536	0.614	6.44

TABLE VIII (cont.)

No.	SIZE l X w in.	ENGINEERING YIELD STRAIN in/in.	TENSILE STRENGTH psi E +04	YIELD STRENGTH psi E +04	MODULUS OF ELASTICITY psi E +05
Thickness : 1.43 E -03 in.					
15.	7.0 X 4.5	0.00560	1.233	0.493	9.10
16.	7.0 X 4.5	0.00896	1.702	0.681	7.57
17.	7.0 X 4.5	0.00856	1.382	0.552	6.45
18.	7.0 X 4.5	0.00976	1.882	0.752	7.70

TABLE IX

TENSILE PROPERTIES OF POLYPROPYLENE IN TRANSVERSE DIRECTION

No.	SIZE l X w in.	ENGINEERING YIELD STRAIN in/in.	TENSILE STRENGTH psi E +04	YIELD STRENGTH psi E +03	MODULUS OF ELASTICITY psi E +05
Thickness : 0.042 in.					
1.	8.0 X 1.0	0.0045	2.978	0.677	1.493
2.	8.0 X 1.0	0.0038	1.758	0.406	1.069
3.	8.0 X 2.0	0.0030	1.068	0.417	1.389
Thickness : 1.43 E -03 in.					
1.	4.5 X 4.5	0.0082	1.300	2.02	2.470
2.	4.5 X 4.5	0.0242	1.567	2.43	1.006
3.	4.5 X 4.5	0.0189	1.057	1.64	0.865
4.	4.5 X 4.5	0.0115	0.607	0.94	0.815
5.	4.5 X 4.5	0.0063	0.954	1.48	2.360
6.	4.5 X 4.5	0.0048	1.111	1.72	3.622
7.	4.5 X 4.5	0.0043	0.301	0.47	1.074
8.	4.5 X 4.5	0.0104	1.584	2.46	2.364
9.	4.5 X 4.5	0.0068	1.389	2.15	3.142

TABLE X

TENSILE PROPERTIES OF ALUMINUM COATED PAPER IN LONGITUDINAL DIRECTION

No.	SIZE l X w in.	ENGINEERING STRAIN in/in. E -02	TEAR STRENGTH psi E +05	YIELD STRENGTH psi E +04	MODULUS OF ELASTICITY psi E +05
Thickness : 0.024 in.					
1.	7.0 X 5.0	3.084	0.103	____	3.34
2.	7.0 X 5.0	2.800	0.094	____	3.44
3.	7.0 X 5.0	2.500	0.096	____	3.84
4.	7.0 X 5.0	3.210	0.103	____	3.21
5.	7.0 X 5.0	2.930	0.112	____	3.82
6.	7.0 X 5.0	3.163	0.097	____	3.07
7.	7.0 X 5.0	3.400	0.128	____	3.76

TABLE XI

TENSILE PROPERTIES OF ALUMINUM COATED PAPER IN TRANSVERSE DIRECTION

No.	SIZE l X w in.	ENGINEERING STRAIN in/in. E -02	TEAR STRENGTH psi E +04	YIELD STRENGTH psi E +04	MODULUS OF ELASTICITY psi E +04
Thickness : 0.024 in.					
1.	5.0 X 4.0	4.570	0.0768	____	1.68
2.	5.0 X 4.0	2.921	0.0368	____	1.26
3.	5.0 X 4.0	2.020	0.0359	____	1.78
4.	5.0 X 4.0	3.062	0.0435	____	1.42
5.	5.0 X 4.0	2.520	0.0312	____	1.24

TABLE XII

TENSILE PROPERTIES OF ALUMINUM FOIL IN LONGITUDINAL DIRECTION

No.	SIZE 1 X w in.	ENGINEERING YIELD STARIN in/in.	TENSILE STRENGTH psi E +03	YIELD STRENGTH psi E +03	MODULUS OF ELASTICITY psi E +05
1.	12.0 X 12.0	0.0111	5.01	2.00	1.810
2.	12.0 X 12.0	0.0119	4.78	1.84	1.537
3.	12.0 X 12.0	0.0105	4.95	1.83	1.742
4.	9.00 X 12.0	0.0176	4.73	1.89	1.070
5.	9.00 X 12.0	0.0159	4.55	1.90	1.188
6.	9.00 X 12.0	0.0166	4.83	1.93	1.161
7.	6.00 X 12.0	0.0223	4.77	2.07	0.929
8.	6.00 X 12.0	0.0186	5.13	2.05	1.100
9.	6.00 X 12.0	0.0164	4.72	1.69	1.031

TABLE XIII

TENSILE PROPERTIES OF ALUMINUM FOIL IN TRANSVERSE DIRECTION

No.	SIZE l X w in.	ENGINEERING YIELD STRAIN in/in.	TENSILE STRENGTH psi E +03	YIELD STRENGTH psi E +03	MODULUS OF ELASTICITY psi E +05
1.	6.0 X 12.0	0.0175	4.22	0.843	0.480
2.	6.0 X 12.0	0.0116	3.98	0.675	0.582
3.	6.0 X 12.0	0.0105	3.27	0.727	0.691
4.	9.0 X 12.0	0.0078	4.58	0.822	1.050
5.	9.0 X 12.0	0.0096	4.33	0.866	0.900
6.	9.0 X 12.0	0.0092	4.92	0.895	0.978
7.	6.0 X 9.00	0.0100	2.61	0.435	0.435
8.	6.0 X 9.00	0.0118	2.73	0.546	0.464
9.	6.0 X 9.00	0.0102	3.42	0.571	0.558
10.	9.0 X 9.00	0.0078	4.22	0.703	0.893
11.	9.0 X 9.00	0.0116	4.31	0.960	0.830
12.	9.0 X 9.00	0.0109	4.26	0.852	0.779

TABLE XIV

TENSILE PROPERTIES OF POLYETHYLENE IN LONGITUDINAL DIRECTION

No.	SIZE l X w in.	ENGINEERING YIELD STRAIN in/in.	TENSILE STRENGTH psi E +03	YIELD STRENGTH psi E +02	MODULUS OF ELASTICITY psi E +04
1.	8.0 X 1.0	0.01197	5.59	2.795	2.335
2.	8.0 X 1.0	0.01215	5.87	2.668	2.196
3.	8.0 X 1.0	0.01423	4.91	2.737	2.617
4.	8.0 X 1.0	0.01068	4.97	2.485	2.325

TABLE XV

TENSILE PROPERTIES OF KRAFT PAPER IN LONGITUDINAL DIRECTION

No.	SIZE l X w in.	ENGINEERING STRAIN in/in.	TEAR STRENGTH psi E +03	YIELD STRENGTH psi E +04	MODULUS OF ELASTICITY psi E +05
1.	7.0 X 2.1	0.0100	1.79	_____	1.79
2.	7.0 X 2.1	0.0091	1.58	_____	1.73
3.	7.0 X 2.1	0.0087	1.24	_____	1.43
4.	7.0 X 2.1	0.0096	1.83	_____	1.90

APPENDIX B

TYPICAL MATERIAL PROPERTIES

TABLE XVI

TYPICAL PROPERTIES OF POLYETHYLENE FILMS

PROPERTIES	LOW & MEDIUM DENSITY (POLYETHYLENE HOMOPOLYMERS)		HIGH DENSITY
	BRANCHED	LINEAR	
PROCESSING			
1. Melting Point (Tm c) crystalline	106 - 115	122 - 124	130 - 137
2. Processing Temperature Range F I : Injection E : Extrusion	I:300-450 E:250-450	I:350-500 E:450-600	I:350-500 E:350-525
MECHANICAL			
3. Tensile Strength at break p.s.i.	1200-4500	1900-4000	3200-4500
4. Elongation at break %	100-650	100-950	10-1200
5. Tensile Yield Strength p.s.i.	1300-2100	1400-2800	3800-4800
6. Tensile Modulus 1000 p.s.i.	25-41	38-75	155-158
THERMAL			
7. Coeff. of linear expansion E -06 in/in/ c	100-220		59-110
PHYSICAL			
8. Specific gravity	0.917-0.932	0.918-0.935	0.952-0.965

Source : Modern Plastics Encyclopedia, 1985-86.

TABLE XVII

TYPICAL PROPERTIES OF POLYPROPYLENE FILMS

PROPERTIES	HOMOPOLYMER	COPOLYMER
PROCESSING		
1. Melting Point (Tm c) crystalline	168	160-168
2. Processing Temperature Range F I: Injection E: Extrusion	I:500-550 E:400-500	I:400-550 E:400-500
MECHANICAL		
3. Tensile Strength at break p.s.i.	4500-6000	4000-5500
4. Elongation at break %	100-600	200-700
5. Tensile Yield Strength p.s.i.	4500-5400	3500-4300
6. Tensile Modulus 1000 p.s.i.	165-225	100-170
THERMAL		
7. Coeff. of linear expansion E -06 in/in/ c	81-100	68-95
PHYSICAL		
8. Specific gravity	0.900-0.910	0.890-0.905

Source : Modern Plastics Encyclopedia, 1985-86.

TABLE XVIII

TYPICAL PROPERTIES OF POLYSTYRENE FILM

PROPERTIES	HIGH & MEDIUM FLOW
PROCESSING	
1. Melting Point (Tg c) amorphous	74-105
2. Processing Temperature Range F C: Compression I: Injection E: Extrusion	C:300-400 I:350-500 E:350-500
MECHANICAL	
3. Tensile Strength at break p.s.i.	5200-7500
4. Elongation at break %	1.2-2.5
5. Tensile Yield Strength p.s.i.	
6. Tensile Modulus 1000 p.s.i.	330-475
THERMAL	
7. Coeff. of linear expansion E -06 in/in/ c	50-83
PHYSICAL	
8. Specific gravity	1.04-1.05

Source : Modern Plastics Encyclopedia, 1985-86.

TABLE XIX

TYPICAL PROPERTIES OF ALUMINUM FOILS

PROPERTIES	AL 1100	AL 1145	AL1199
MECHANICAL PROPERTIES			
1. Tensile strength MPa	75-130	95-140	45-120
2. Yield strength MPa	34-115	41-117	10-115
3. Poisson's ratio	0.33	0.3	___
4. Elastic Modulus	10 E +06	___	9 E +06
THERMAL PROPERTIES			
5. Coeff. of thermal expansion uin/in/ F	13.1-23.6	13.1-23.6	13.6-24.5

Source : ASM Metals Handbook, 1978, Vol. 2.
Hoyt S. L., Metal Properties.
Aluminum Foil in Packaging, Symposium proceedings, 1968.

Note: Above table gives properties for O-state and H-state.

TABLE XX

TYPICAL PROPERTIES OF PAPER FILM

PROPERTIES	KRAFT	PAPER FOIL
MECHANICAL PROPERTIES		
1. Burst strength psi	45	35
2. Internal tear (g)		
MD	100	45
TD	110	55
3. Tensile strength psi		
MD	20	14
TD	13	13
4. Elongation %		
MD	10	8
TD	10	8
5. Rigidity g/1.5 in.		
MD	0.25	0.24
TD	0.24	0.24

Source : Aluminum Foil in Packaging, Symposium proceedings, 1968.

APPENDIX C

COMPUTER DATA AND PLOTS

The NASTRAN finite element data cards used for the computer simulation are given here alongwith the results produced in terms of deformation and stress involved in the respective models.

TABLE XXI

NASTRAN DATA CARDS AND THEIR FUNCTIONS

	DATA CARD	FUNCTION, USE AND LIMITATIONS
1.	GRID	Defines location of the nodal point of the model with an option of individual d.o.f. constraints.
2.	CQUAD2	Connectivity for 2-D homogeneous quadrilateral membrane. Element thickness is global.
3.	PQUAD2	Property identification of the CQUAD2 card. No anisotropy possible
4.	CIHEX1	Connectivity for 3-D linear isoparametric hexahedron element.
5.	PIHEX1	Property identification for CIHEX1 card. Assumes solid model. Anisotropy possible.
6.	MAT1	Material property for linear, isotropic materials.
7.	MAT2	Material property for linear, anisotropic materials.
8.	FORCE	Defines the loading condition on the individual grid points in the direction of given choice. Point loads act on the nodal points leading to averaging effect.
9.	SPC	This card enables the individual grid points to have a constraint i.e. single point constraint of a node is possible and allows x,y,z displacement or even rotation about these axes of any point. Limitation being non global use of this command.

COMPUTER MODEL FOR BOWED ROLLER

2-D ANALYSIS

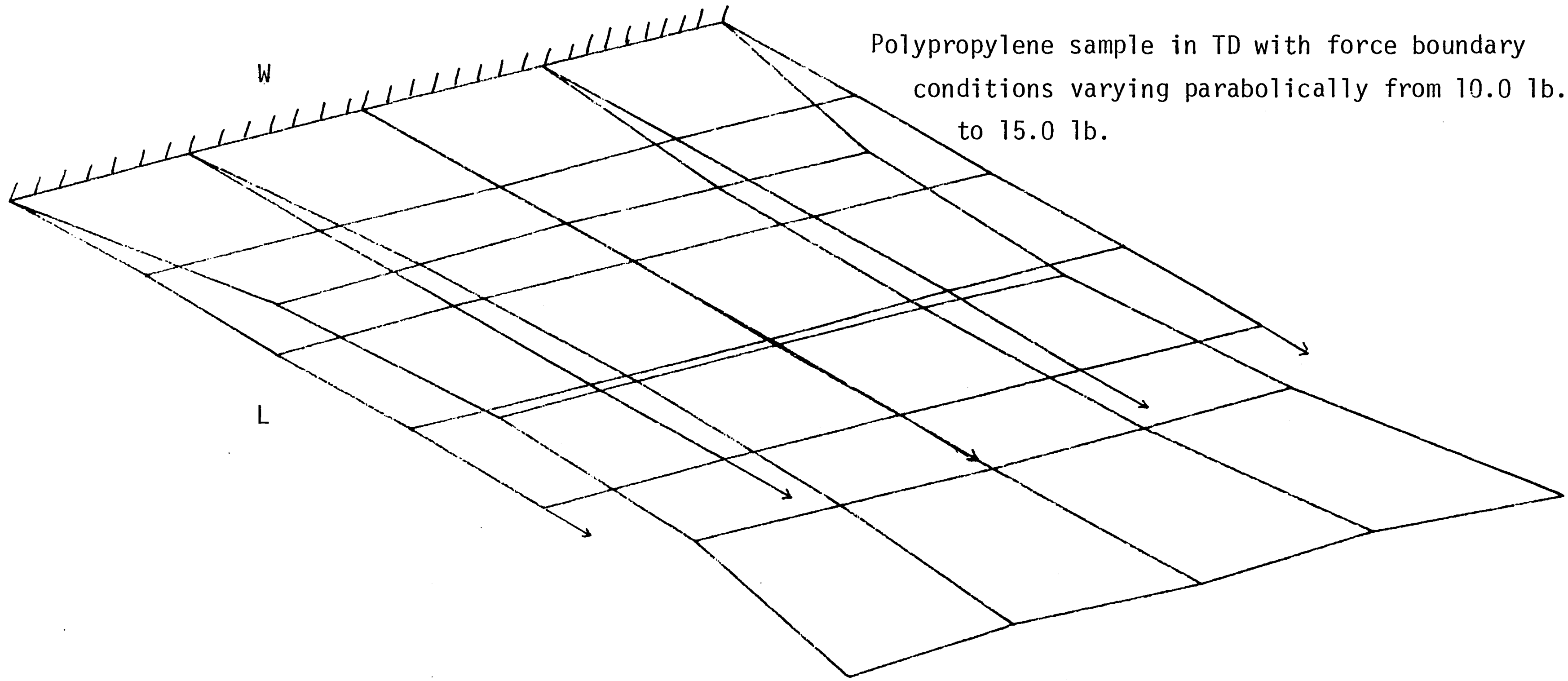


Figure 37. Undeformed and Deformed Shape of Bowed Roller Model: 2-D Analysis

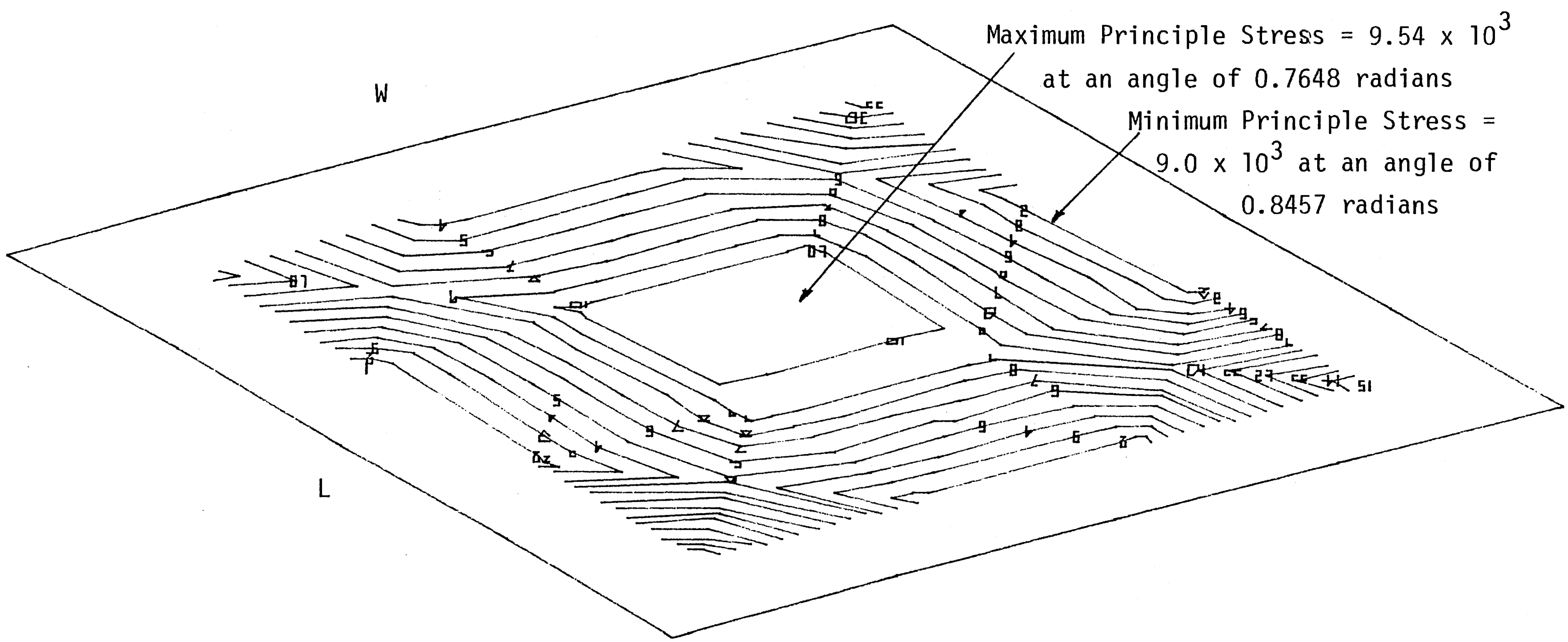


Figure 38. Maximum Principle Stress Contour Plot of Bowed Roller Model: 2-D Analysis

COMPUTER MODEL FOR CONCAVE ROLLER

2-D ANALYSIS

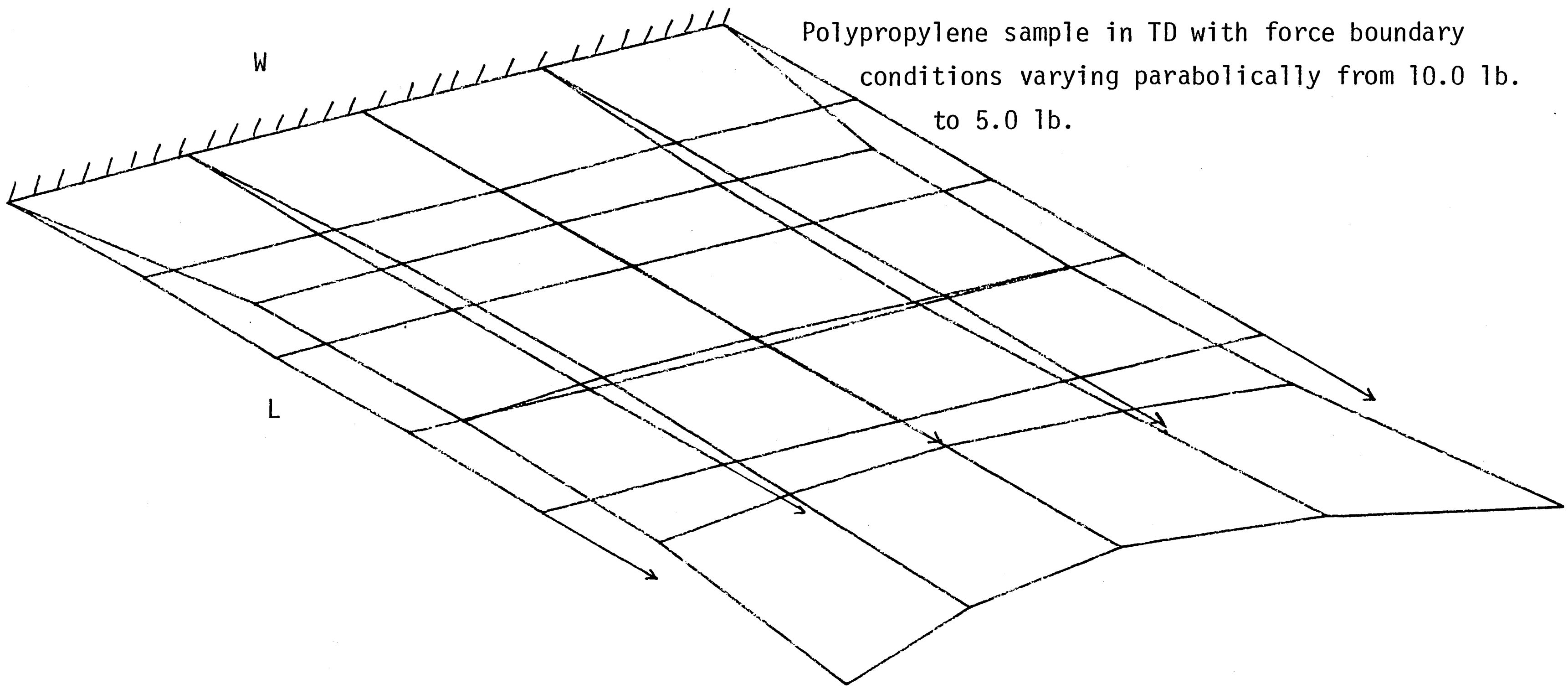


Figure 39. Undeformed and Deformed Shape of Concave Roller Model: 2-D Analysis

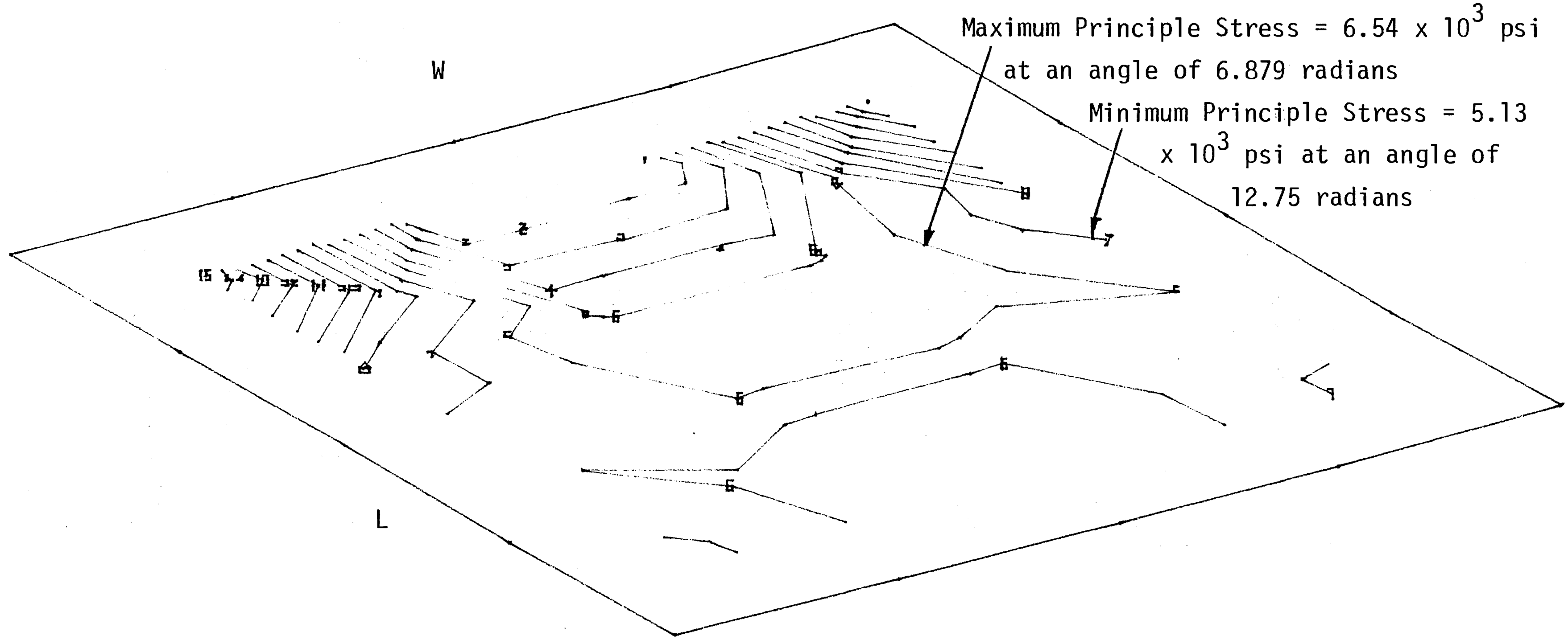


Figure 40. Maximum Principle Stress Contour Plot of Concave Roller Model: 2-D Analysis

COMPUTER MODEL FOR INCLINED ROLLER

2-D ANALYSIS

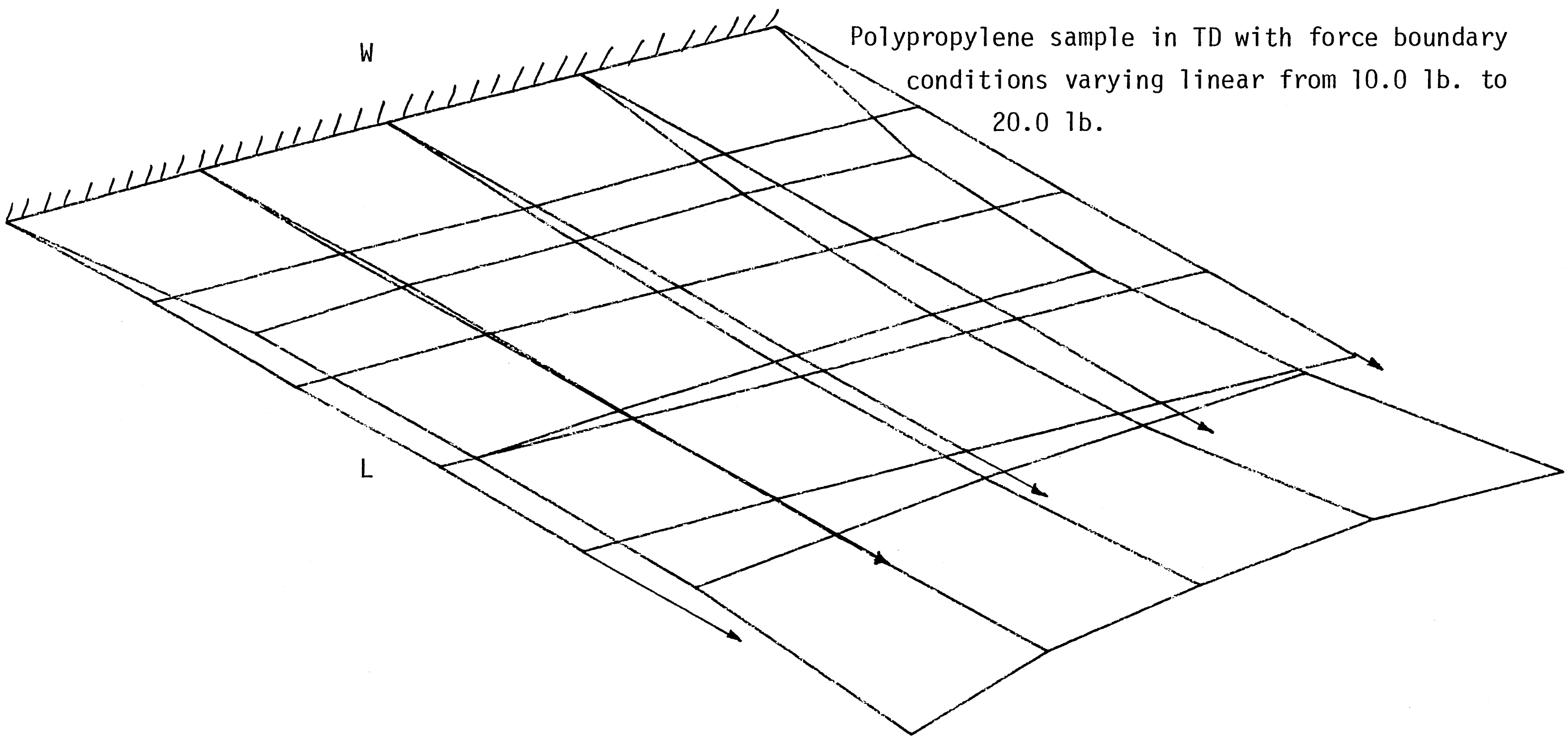


Figure 41. Undeformed and Deformed Shape of Inclined Roller Model: 2-D Analysis

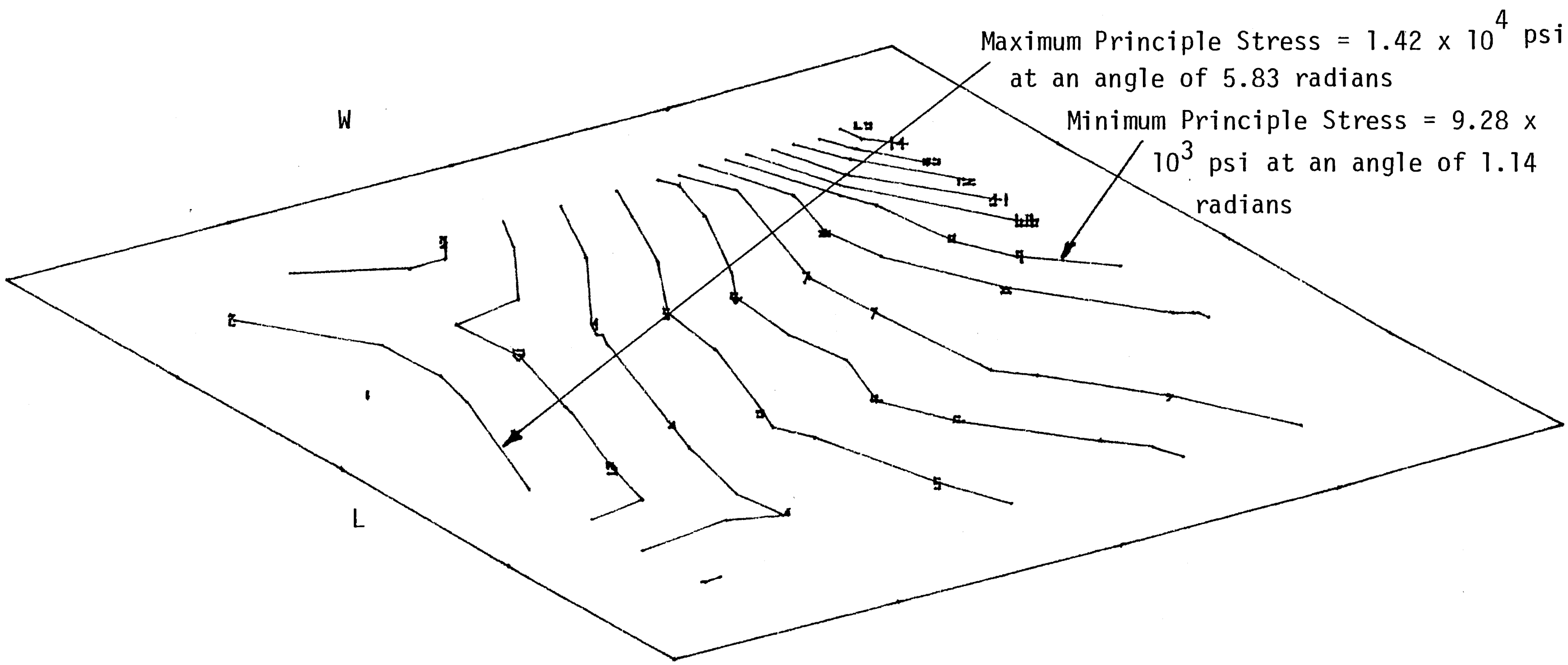


Figure 42. Maximum Principle Stress Contour Plot of Inclined Roller Model: 2-D Analysis

VITA

VINAY K. NILKANTH

Candidate for the Degree of

Master of Science

Thesis: WEB MATERIAL EFFECTS ON WRINKLING INSTABILITY EXPERIMENTAL AND COMPUTER ANALYSIS

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Bombay, India, Aug. 26, 1964, the son of Mr. K. S. and Mrs. S. K. Nilkanth.

Education: Graduated from Balmohan Vidyamandir High School, Bombay, India, in May, 1979; received Bachelor of Engineering Degree in Mechanical Engineering from University of Bombay in June, 1985; received Assosiate Membership of Institute of Engineers in December, 1985; completed requirements for Master of Science degree at Oklahoma State University in May, 1987.

Professional Experience: Research Assistant, Department of Mechanical Engineering, Oklahoma State University, January, 1986, to present.